PYRAMID WAVEFRONT SENSING IN THE ERA OF EXTREME OPTICS

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[3]Steward Observatory, University of Arizona.

ARCS ADVANCING SCIENCE IN AMERICA

LAM LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

cnrs

Aix*Marseille université

ARIZONA

MagAO-X

MagAO

CAAO Center for Astronomical Adaptive Optics

OUTLINE

- Motivation: Exoplanet Imaging
- Extreme Adaptive Optics
  - MagAO-X Update
  - Pyramid Wavefront Sensing
- Three sided Pyramid Wavefront Sensor
  - Operation
  - Mathematics
  - Performance

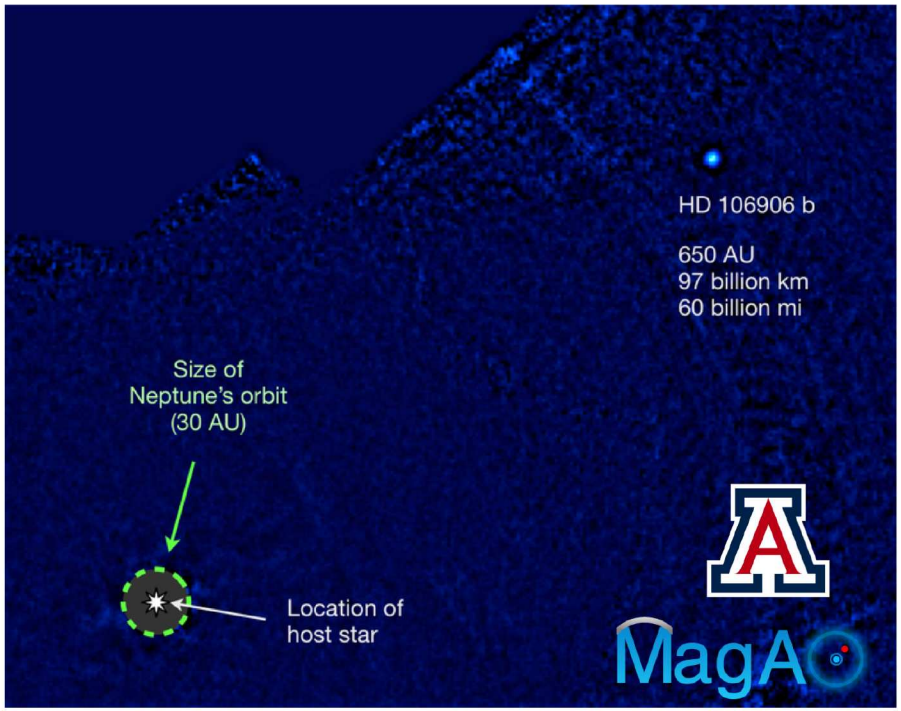
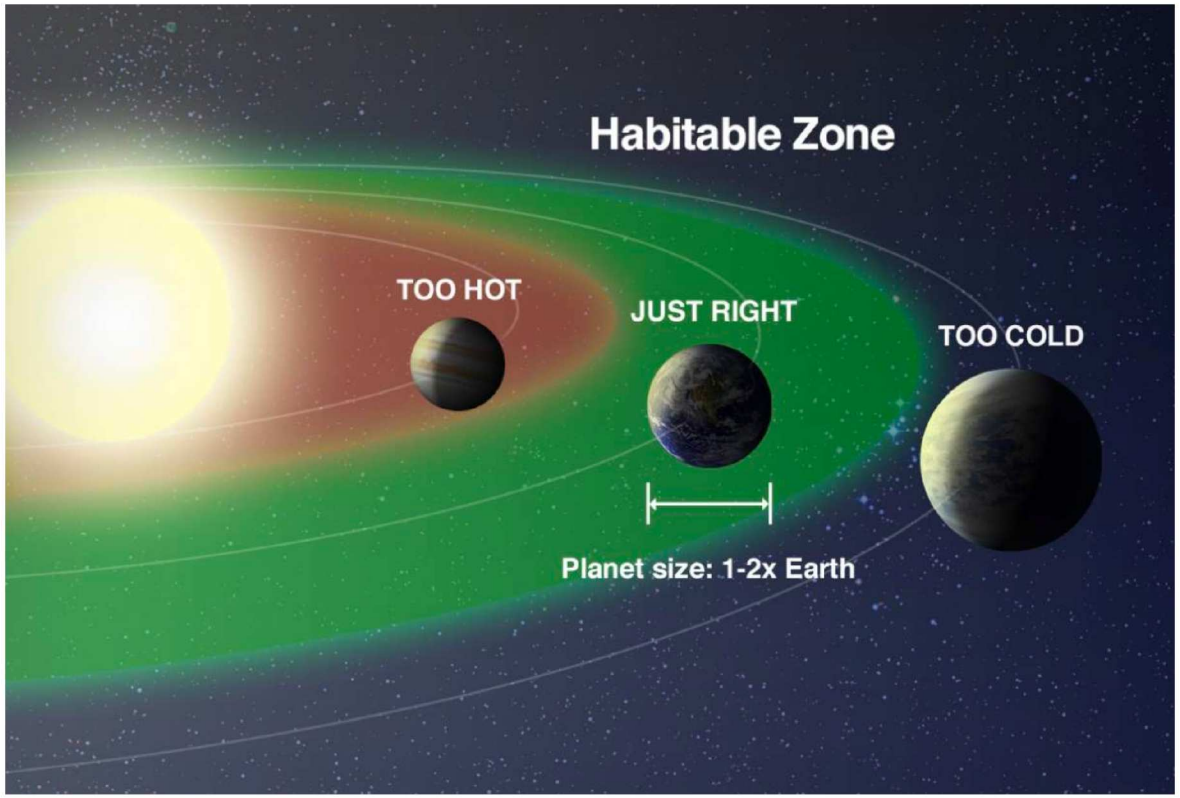


Image Credit, Vanessa Bailey, University of Arizona

THE HABITABLE ZONE

- 4013 exoplanets as of March 21st, 2019
- Region around a star where a planet can support liquid water.
- Earth sized planets in this region are potentially habitable



A TINY BLUE DOT

- Image of Earth from Cassini Space Craft
- How do we characterize a tiny blue dot?

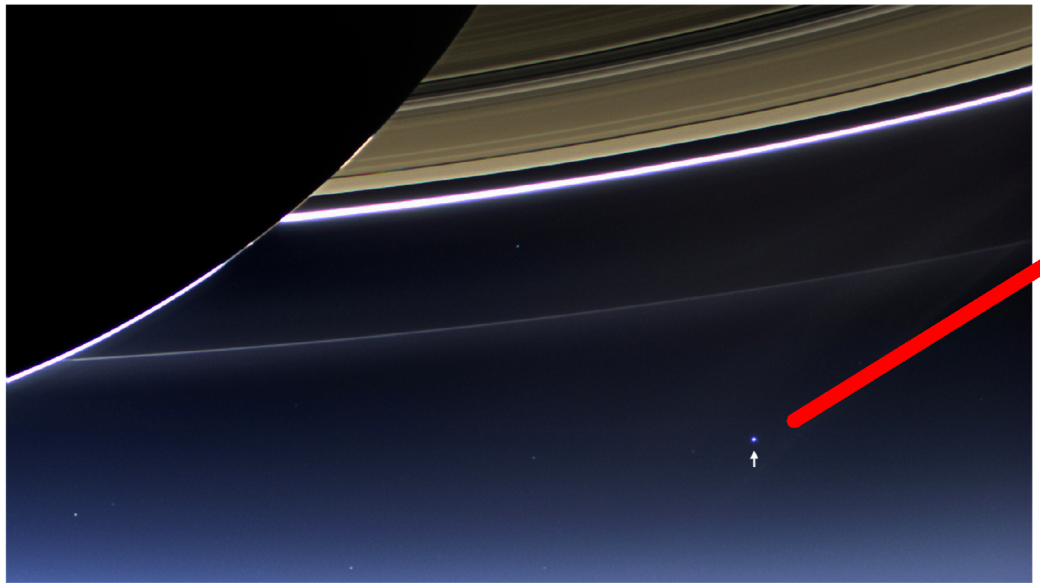


Image credit: NASA Cassini Mission

SOME PROBLEMS: CONTRAST AND TURBULENCE

Contrast

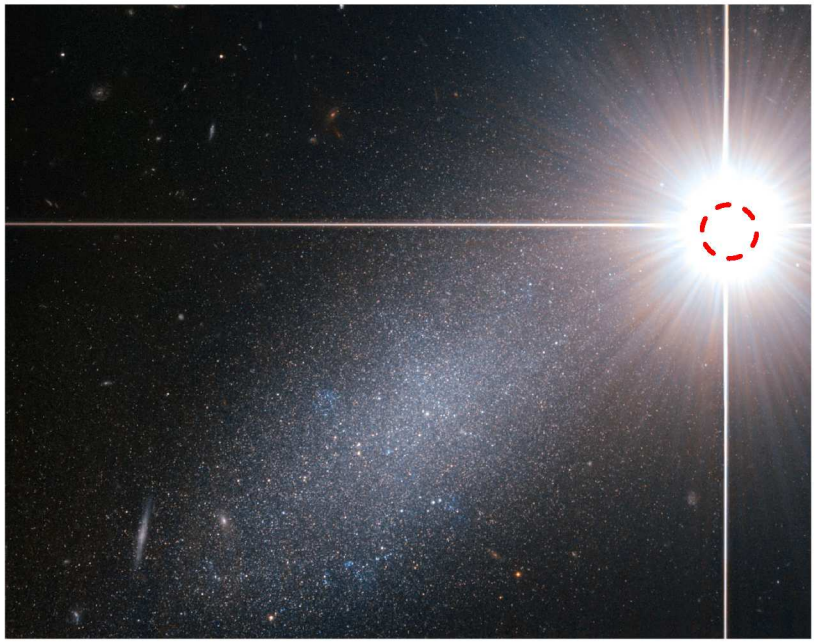


Photo Credit: NASA Hubble Space Telescope

Atmospheric Turbulence

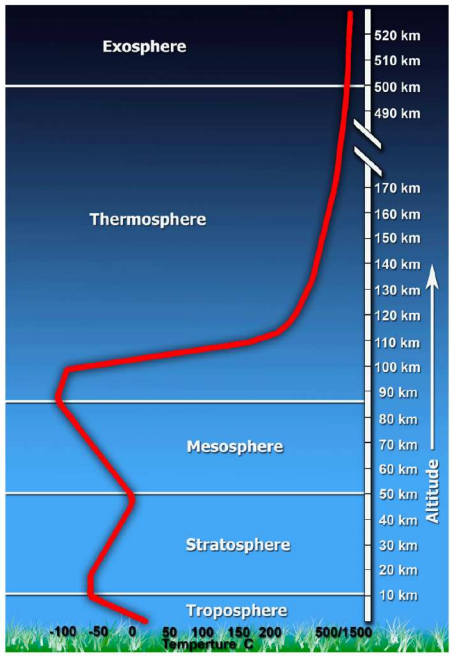
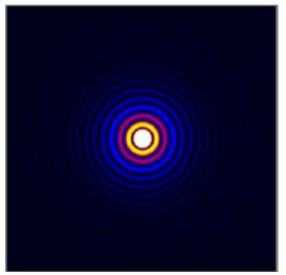
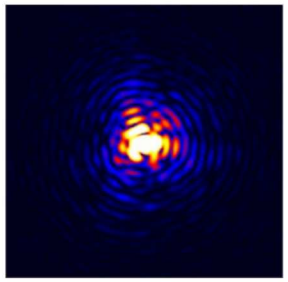


Image Credit: NASA Climate Science Investigations



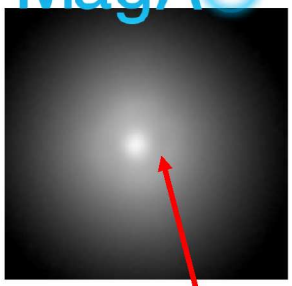
Star without turbulence

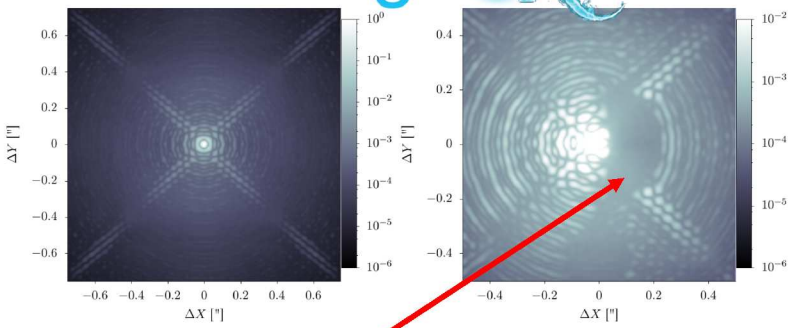


Star with turbulence

DIRECT IMAGING OF EXOPLANETS

MagAO





MagAO-X

c/o Kate Follette

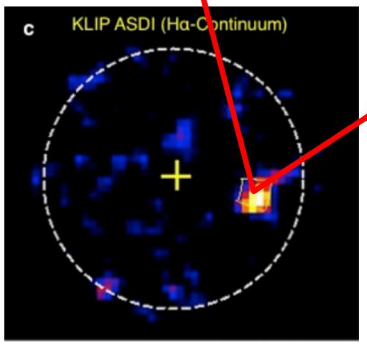
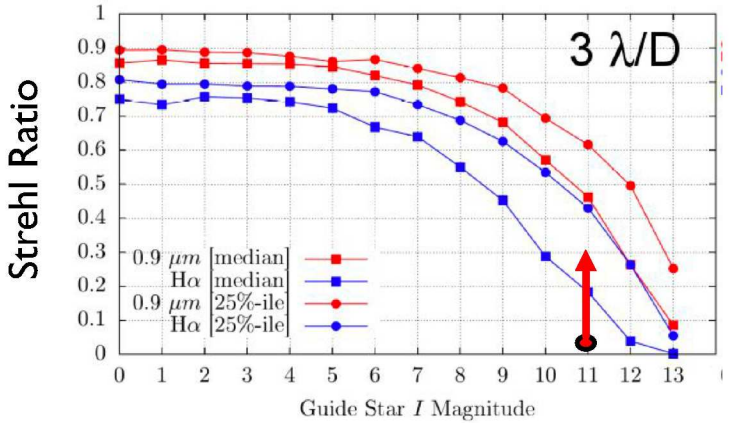
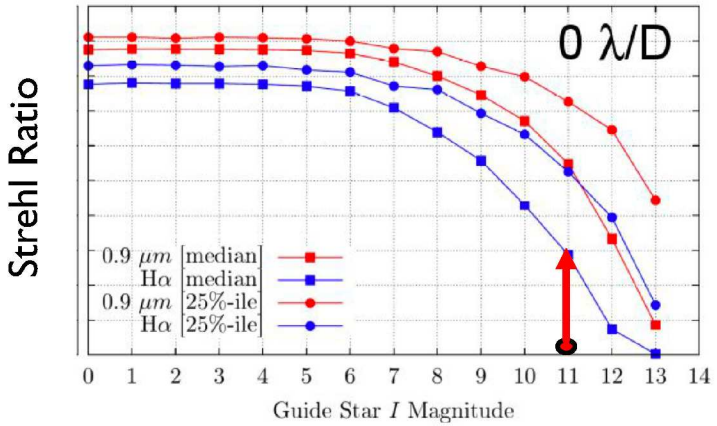


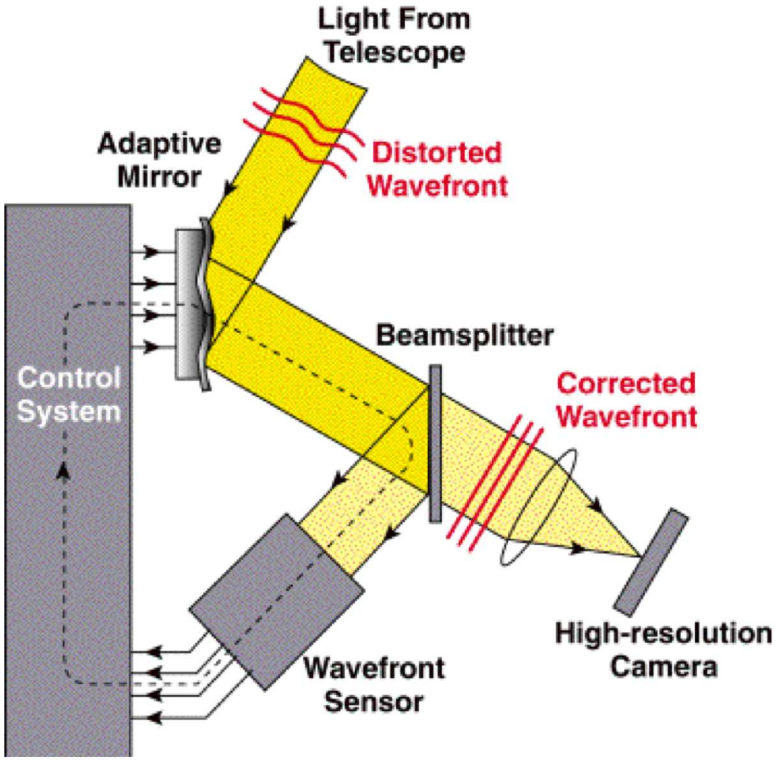
Image of LkCa 15b taken by Kate Follette (Sallum et al., Nature, 2015)

High airmass and 11th mag GS demand high performance.

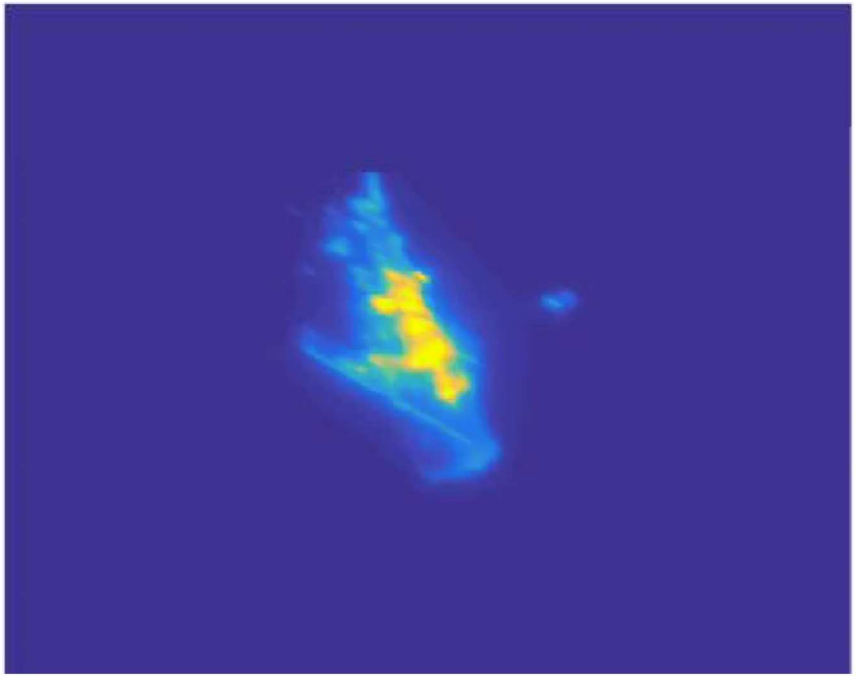




ADAPTIVE OPTICS



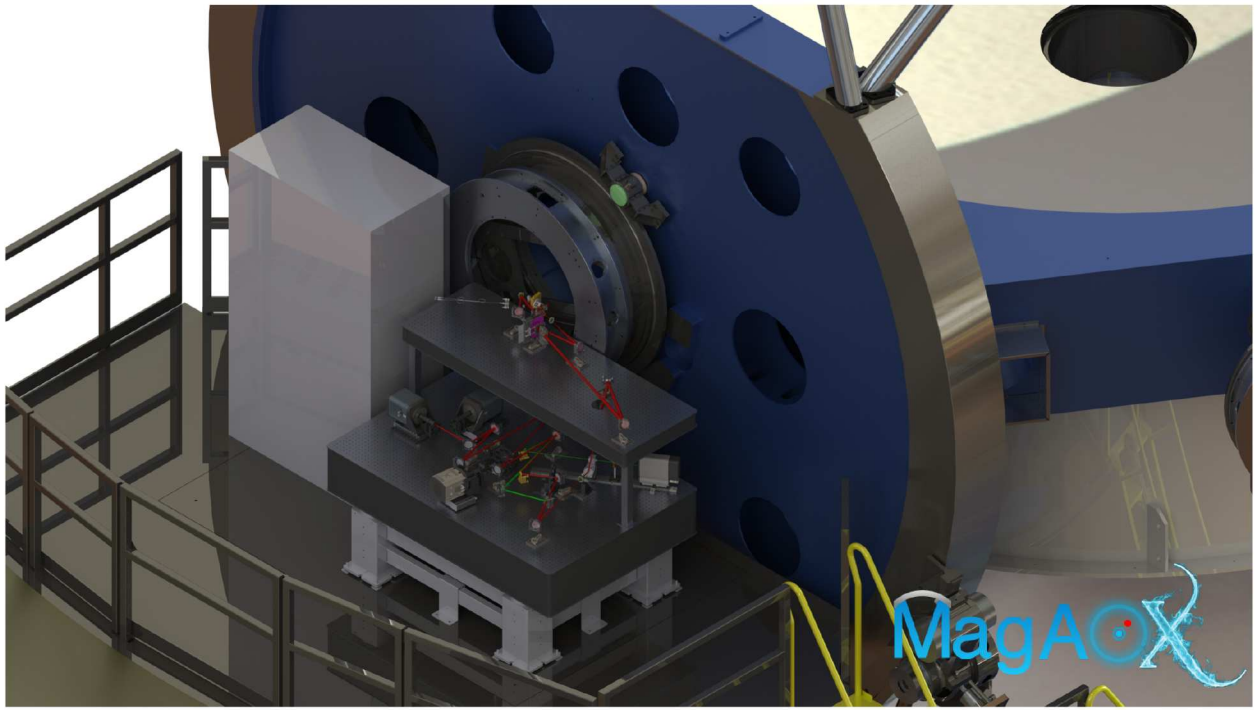
Hubble with AO on/off



EXTREME AO: ONE STEP FURTHER

Key Components:

- Deformable Mirror with high actuator count
- High performance wavefront sensor
- High contrast cornograph



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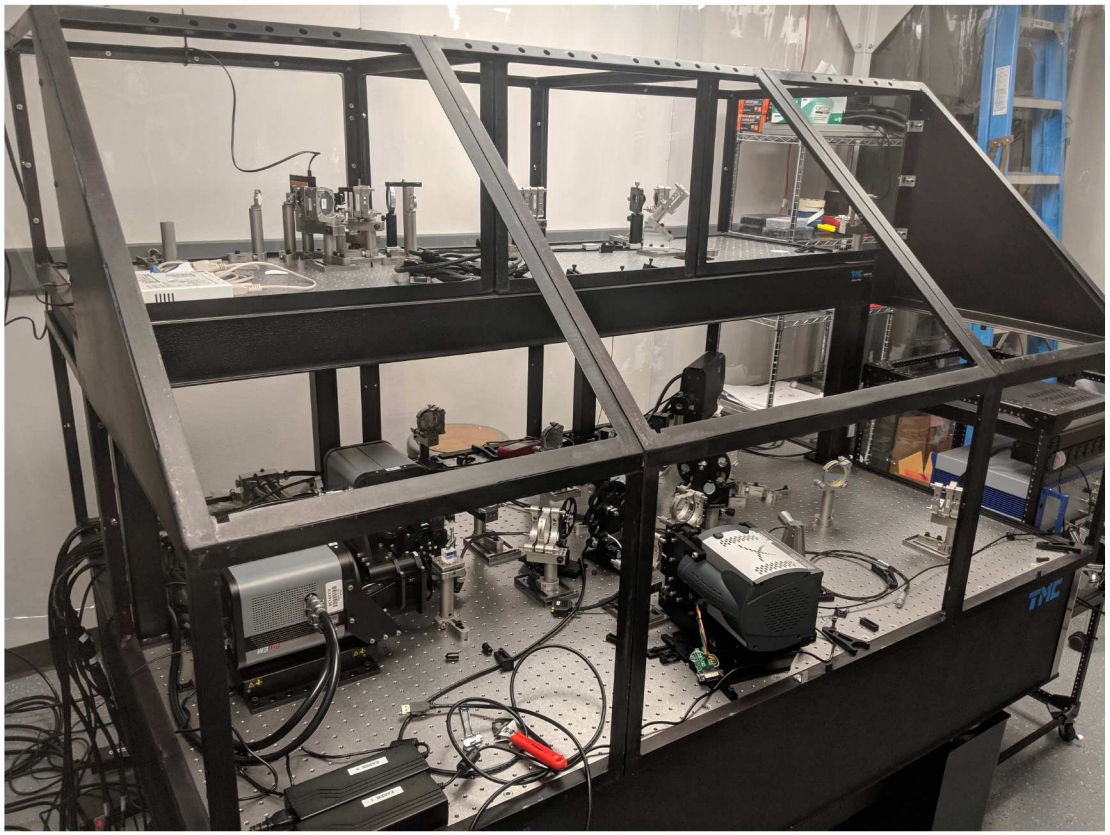
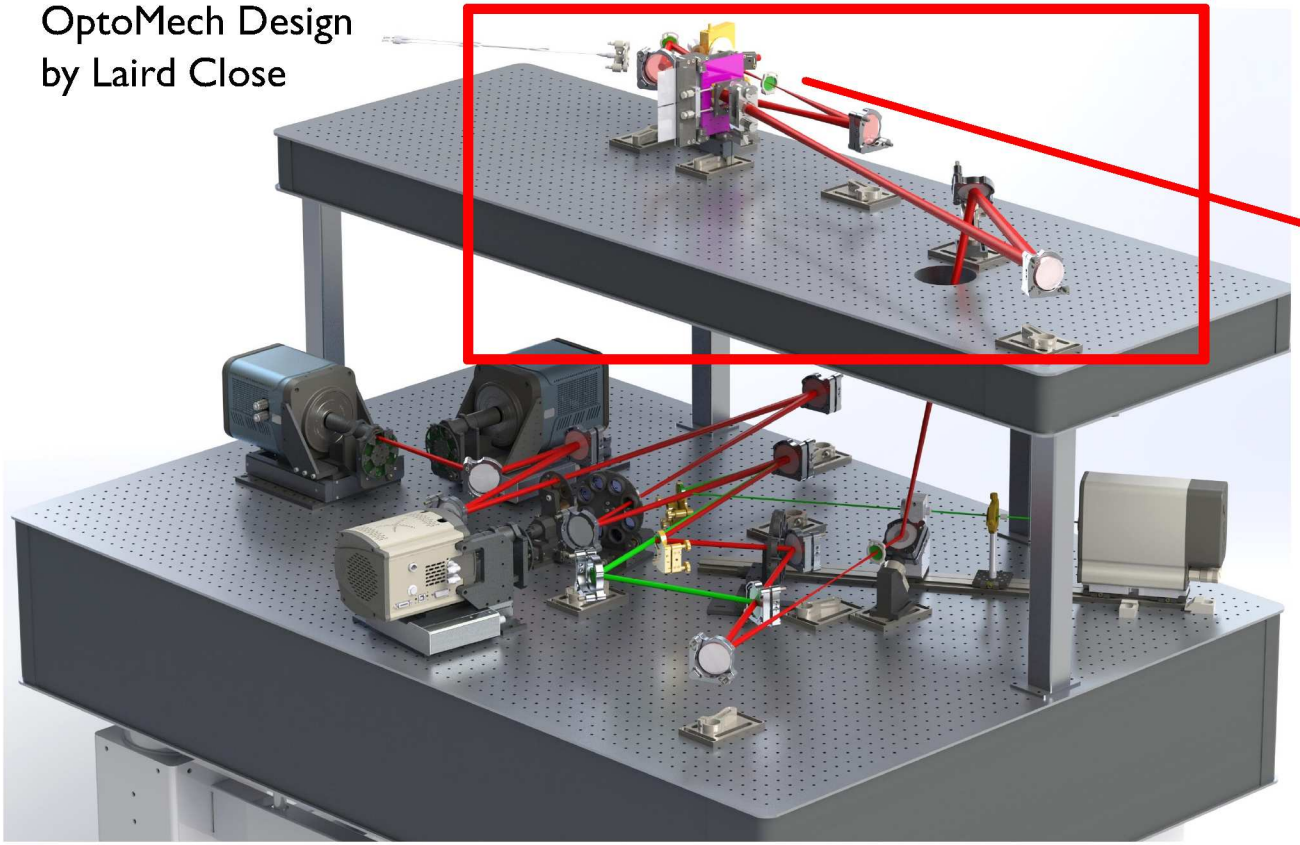
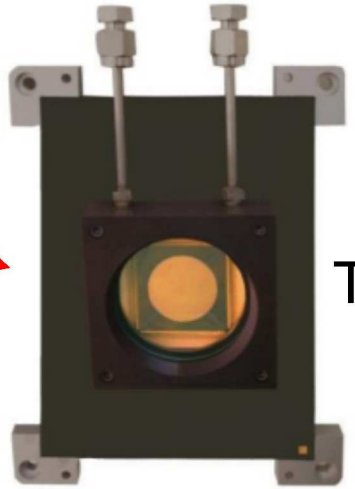


Photo Credit: Jared Males

MAGAO-X: DEFORMABLE MIRROR

OptoMech Design
by Laird Close



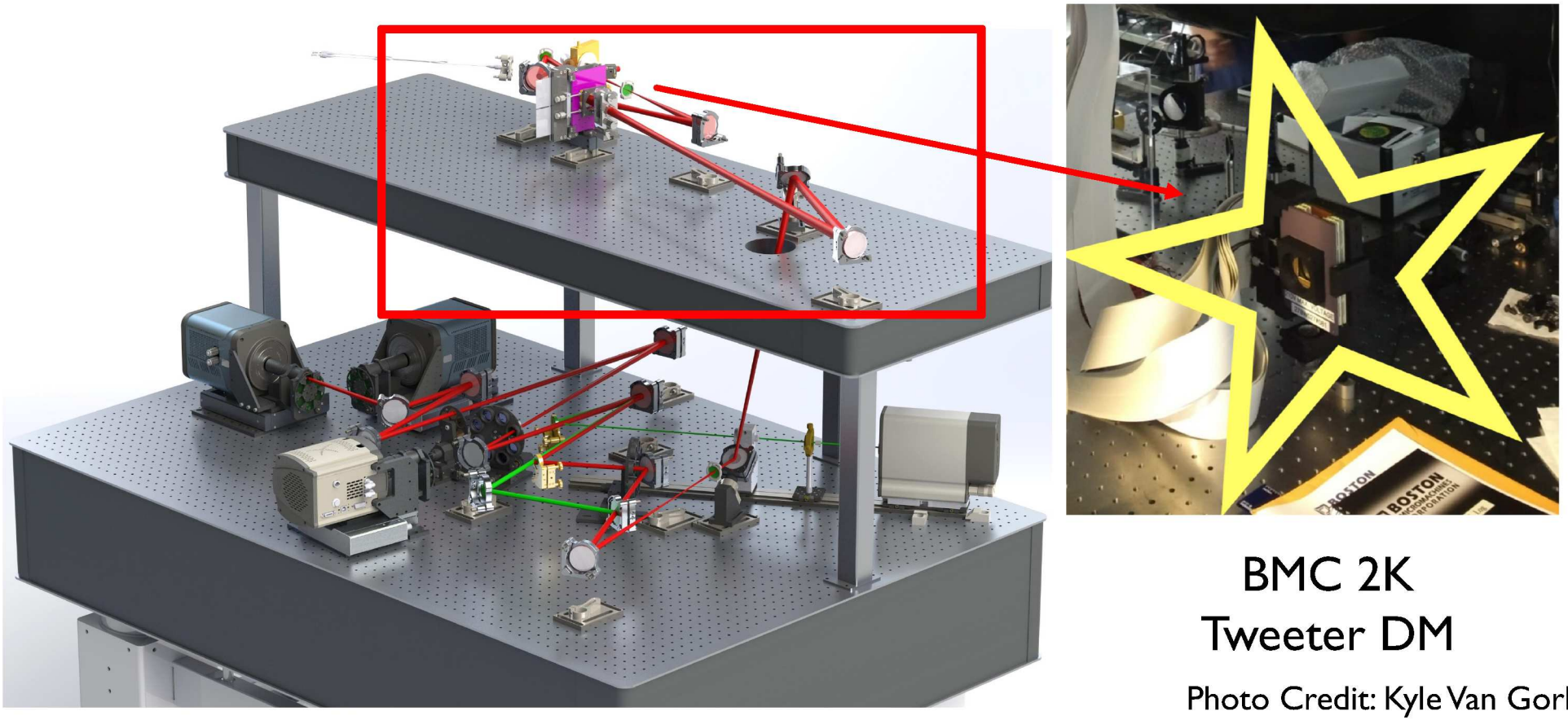


BMC 2K
Tweeter DM

MagAO 585 actuators

MagAO-X 2048 actuators

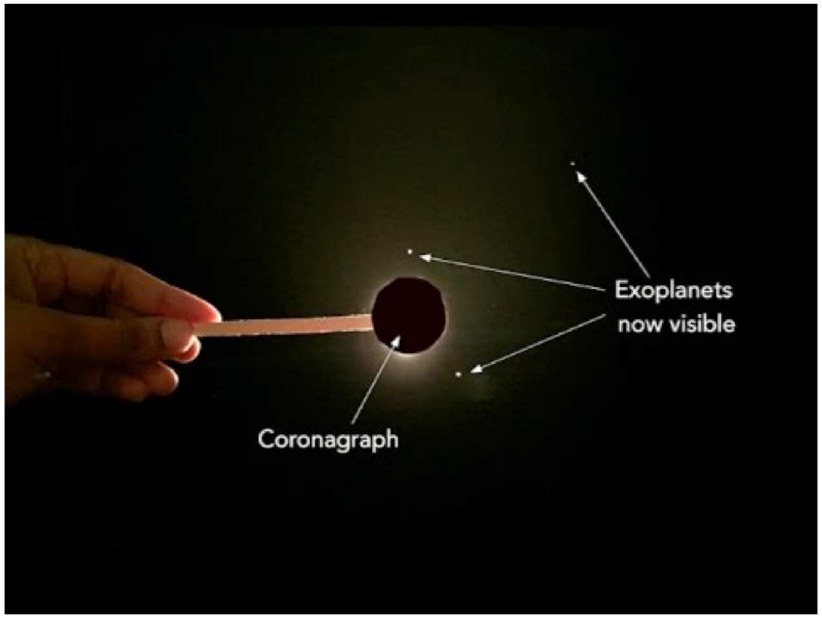
MAGAO-X: DEFORMABLE MIRROR



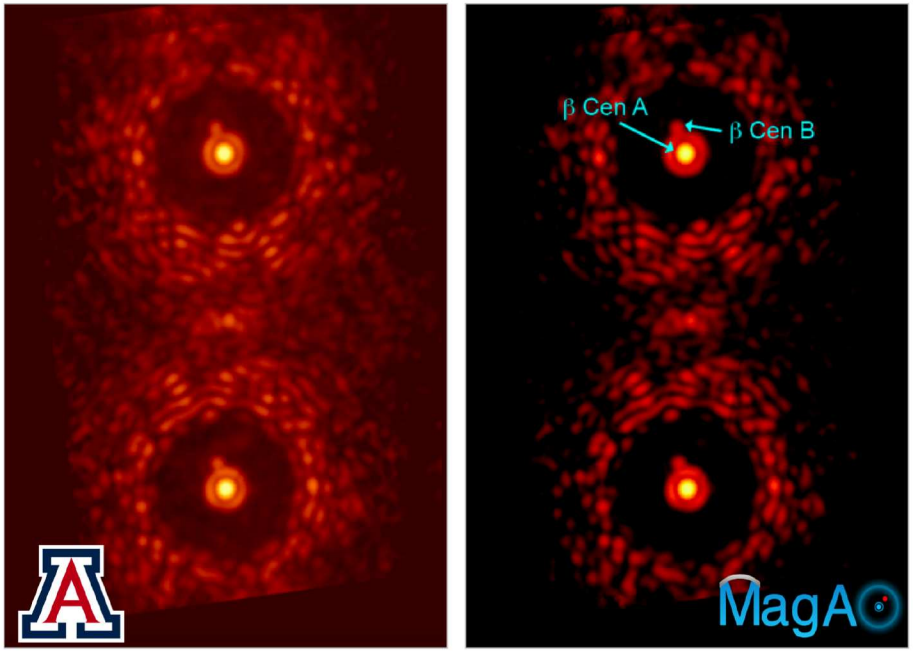
BMC 2K
Tweeter DM

Photo Credit: Kyle Van Gorkom

CORONAGRAPHS

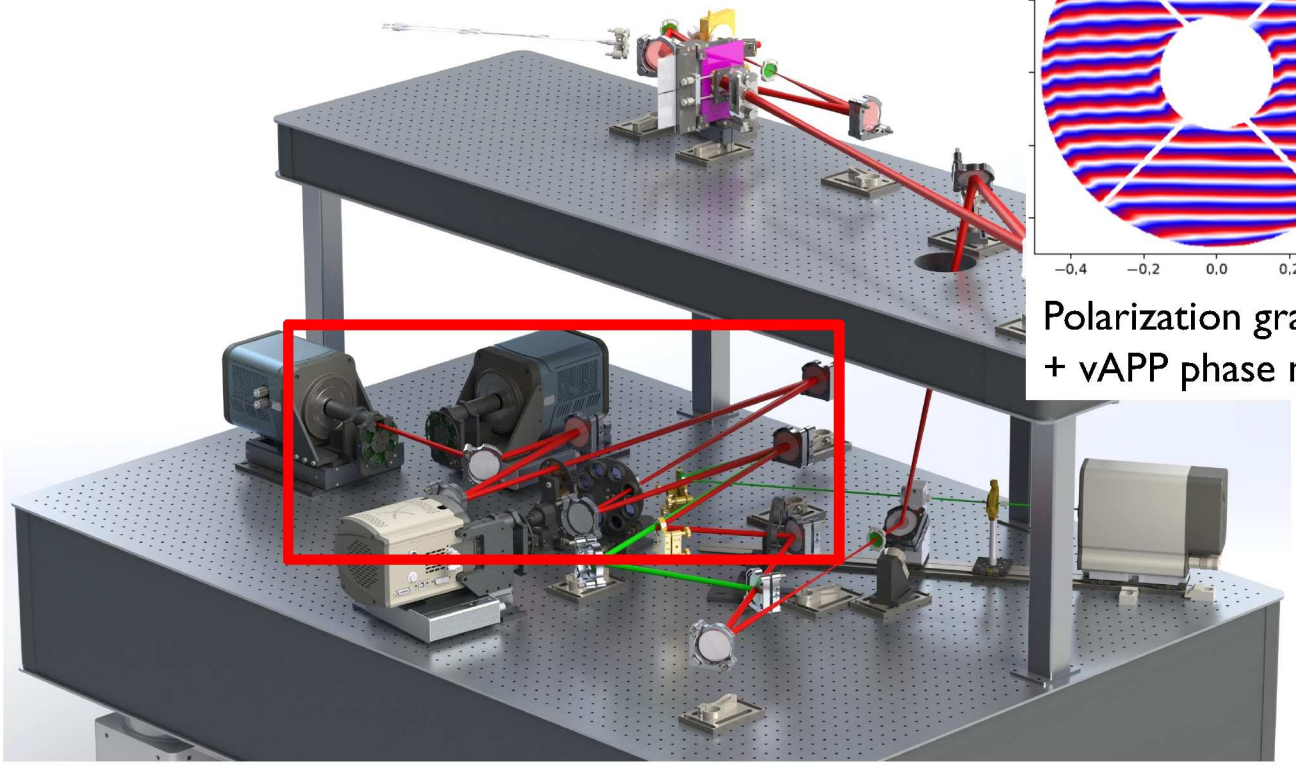


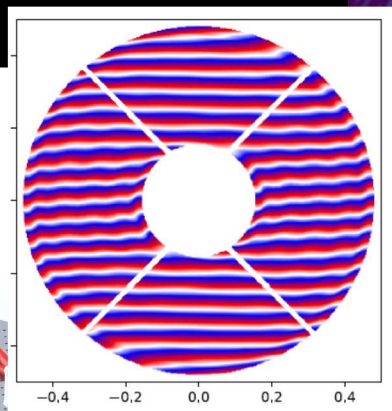
At it's simplest: A dark spot to block the star



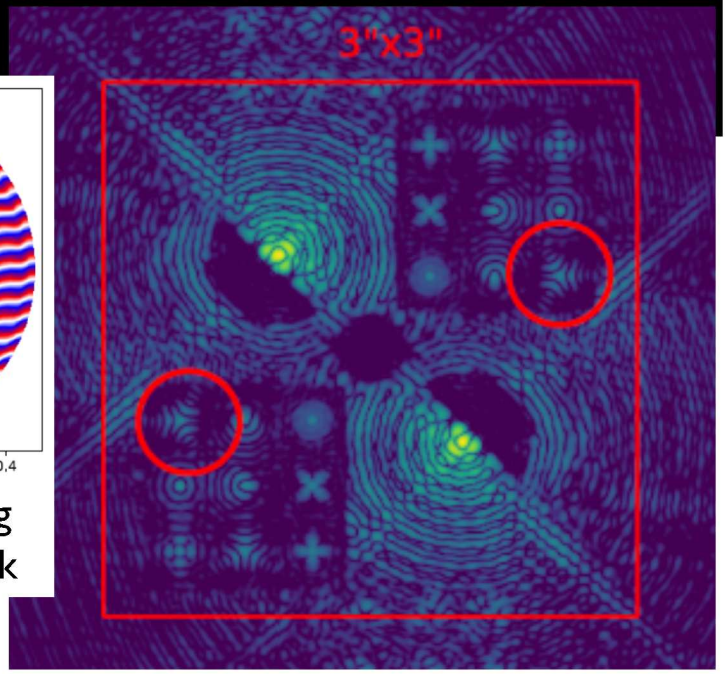
Double image of the star beta Centauri taken through an experimental version of the vector-APP coronagraph installed at MagAO. Binary Companion easily seen. Credit Leiden University, University of Arizona.

MAGAO-X: CORONAGRAPH





Polarization grating
+ vAPP phase mask



vAPP Designed and Manufactured by Univ. of Leiden

MagAO vAPP coronagraph

MagAO-X vAPP +
Focal plane
wavefront sensing

MAGAO-X: CORONAGRAPH

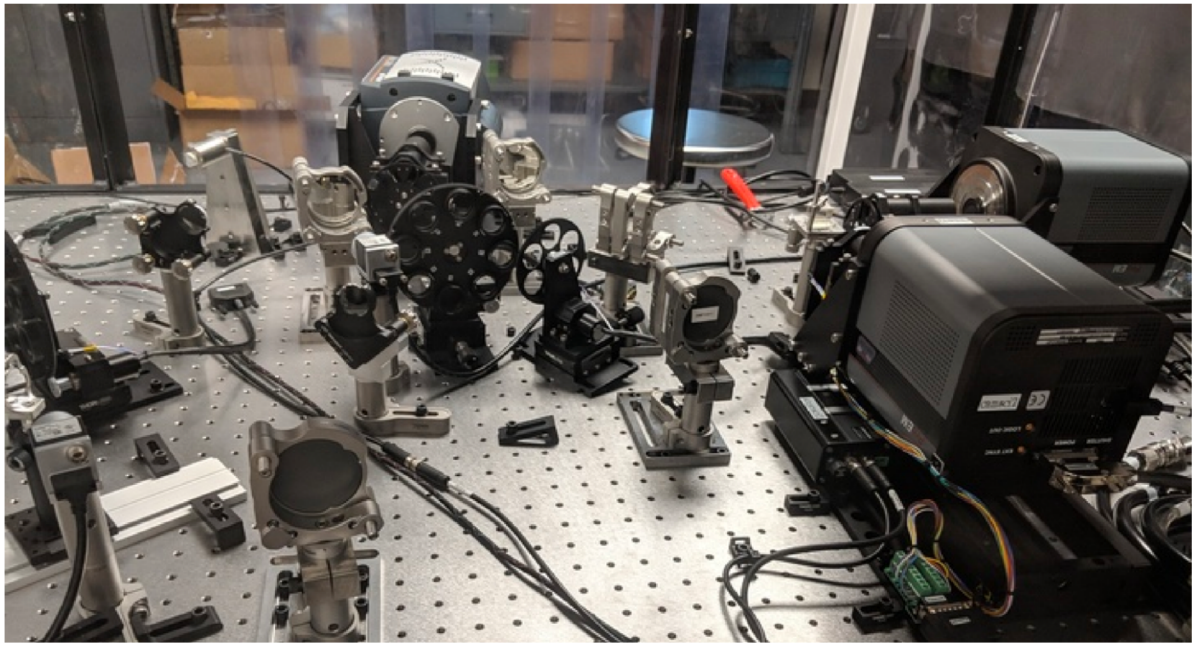
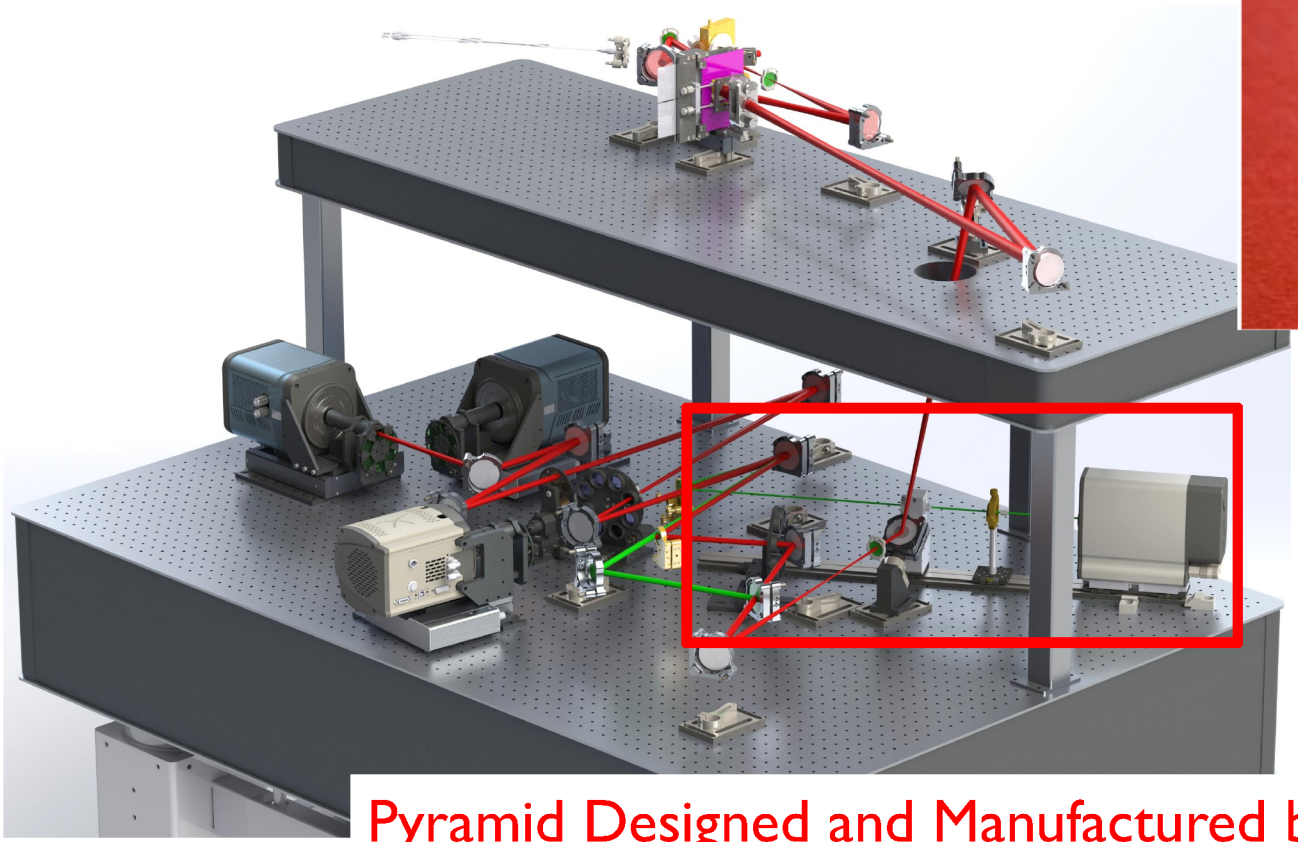


Photo Credit: Jared Males

MAGAO-X: PYRAMID WAVEFRONT SENSOR



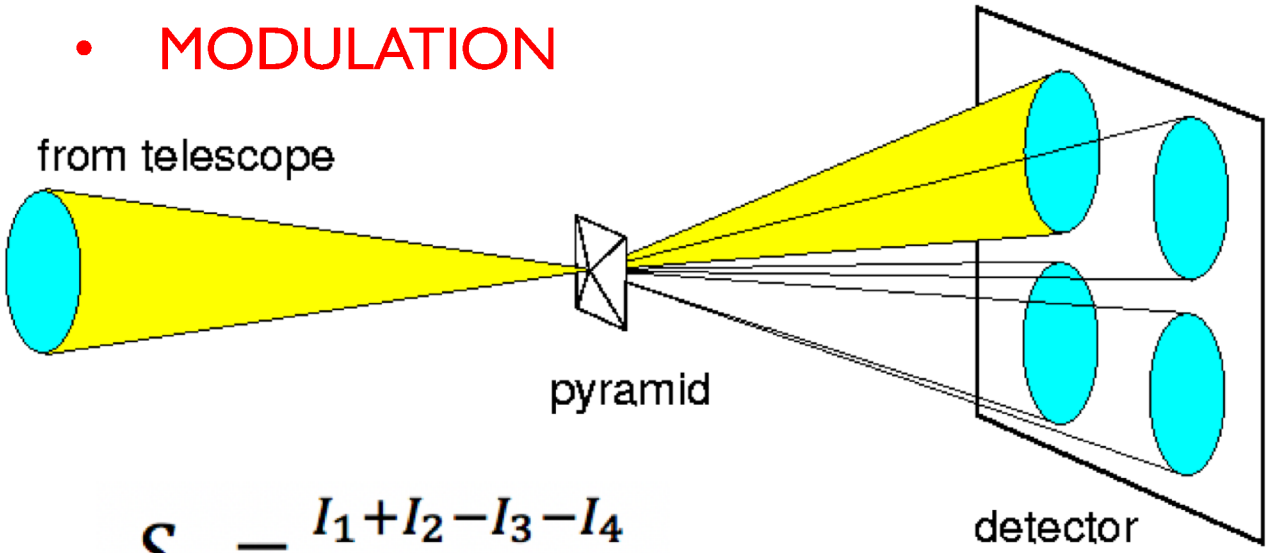
MagAO Pyramid

MagAO-X Pyramid+OCAM2K

Pyramid Designed and Manufactured by Arcetri

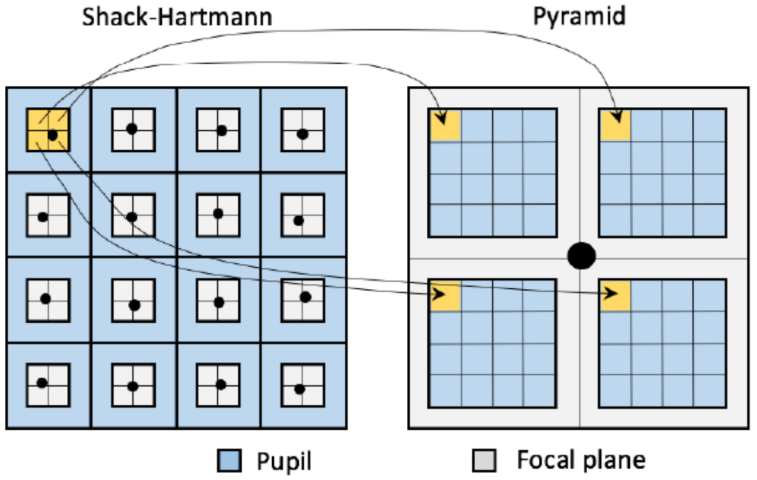
PYRAMID WAVEFRONT SENSING

- MODULATION



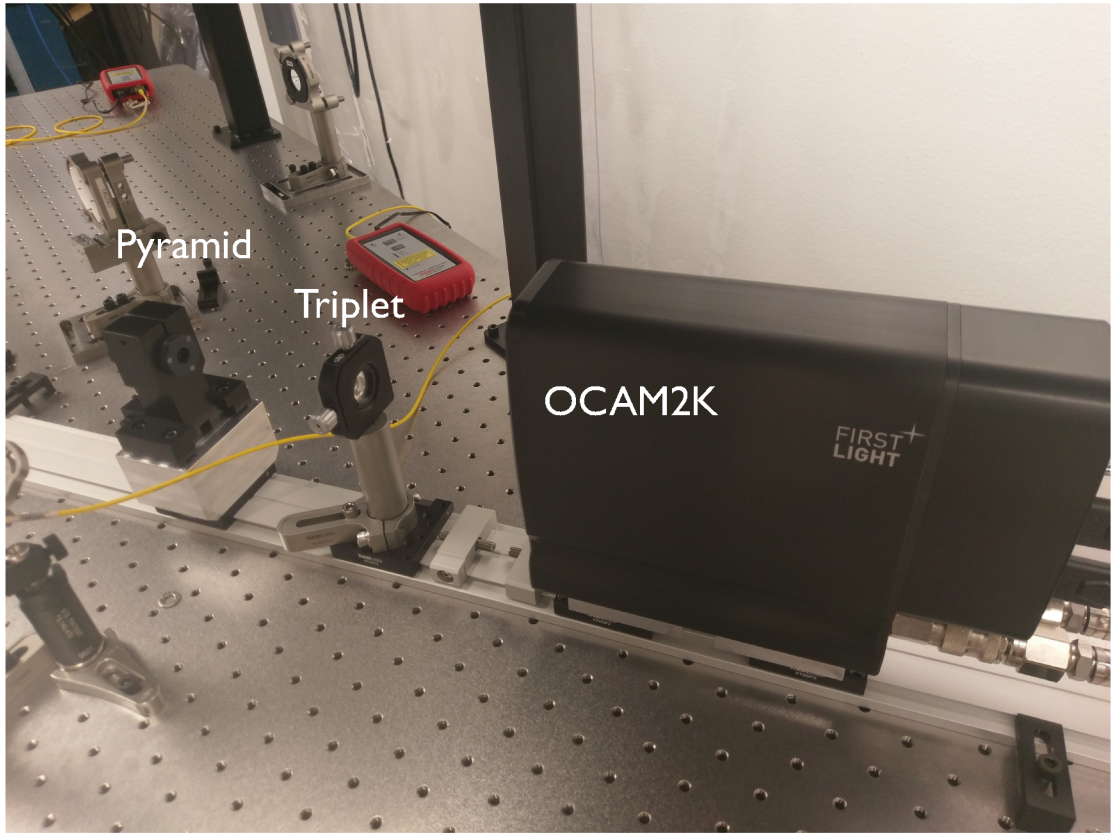
$$S_x = \frac{I_1 + I_2 - I_3 - I_4}{I_1 + I_2 + I_3 + I_4}$$

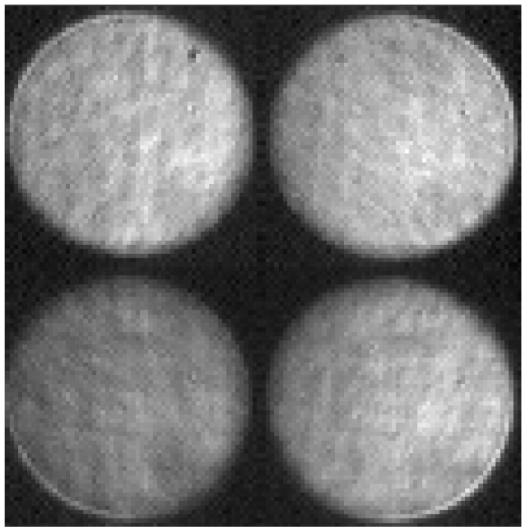
$$S_y = \frac{I_1 - I_2 - I_3 + I_4}{I_1 + I_2 + I_3 + I_4}$$



# of pixels= # of degrees of freedom controlled

MAGAO-X: PYRAMID WAVEFRONT SENSOR

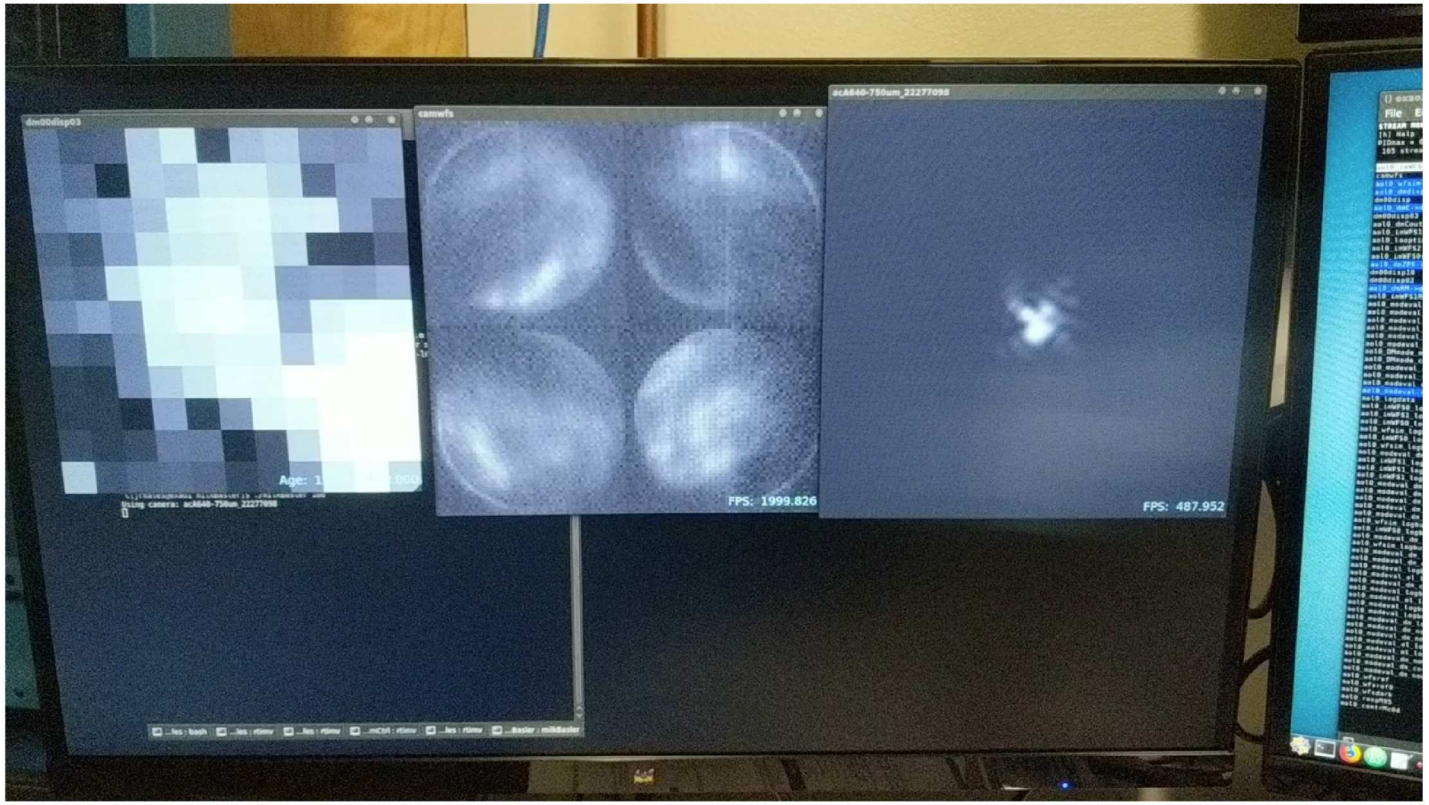




MagAO Pyramid 32x32

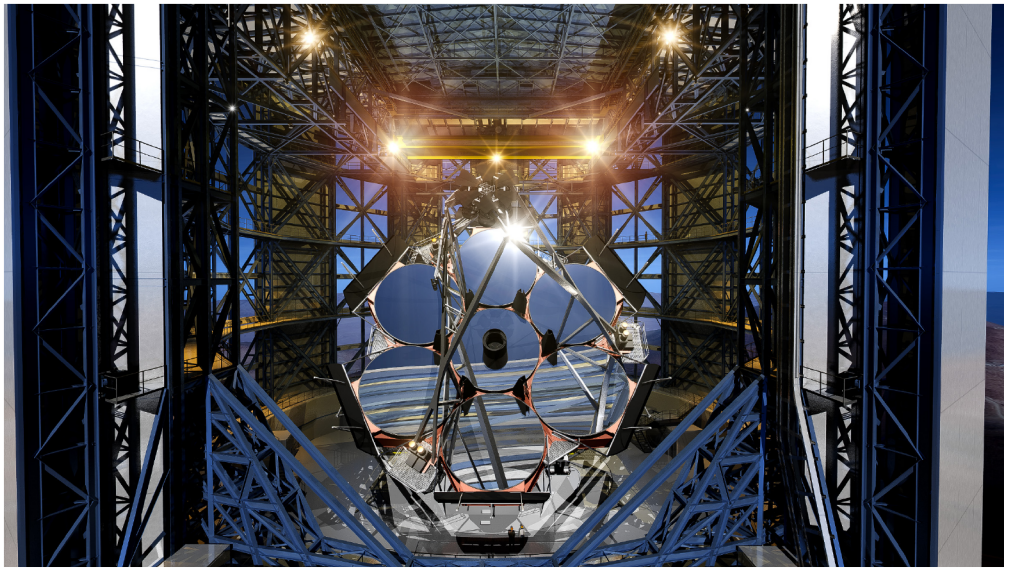
MagAO-X Pyramid+OCAM2K 56x56

CLOSED LOOP!



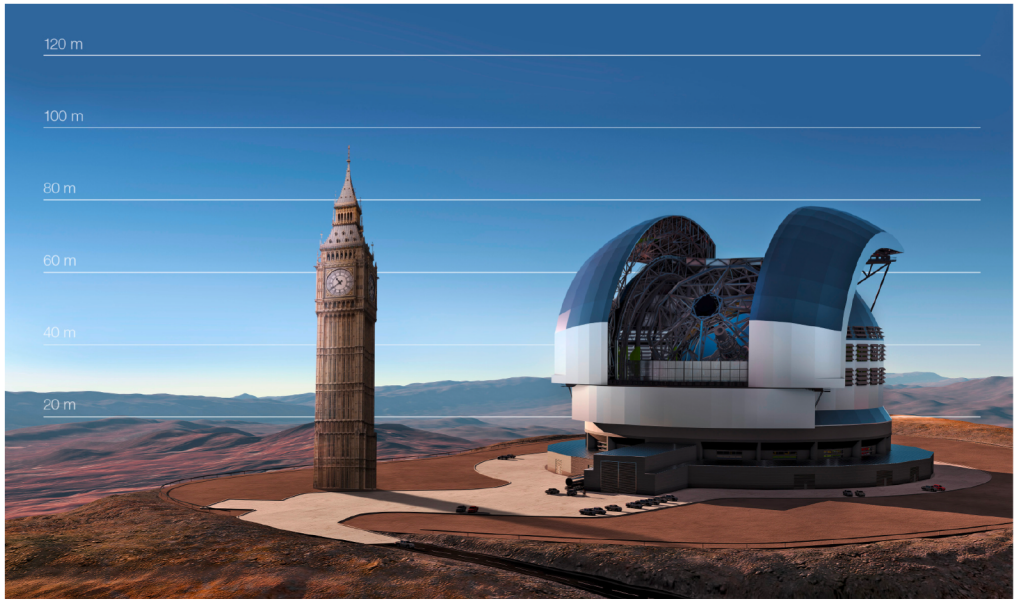
- 2 kHz speed!
- Goal is 3.6kHz

THE EXTREMELY LARGE TELESCOPES



Artist rendering of the Giant Magellan Telescope (GMT).

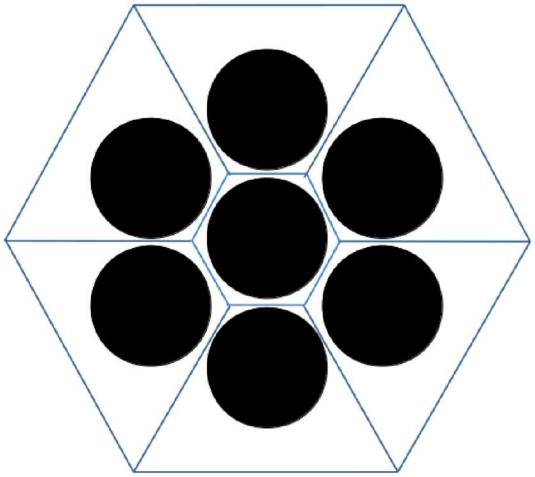
7 mirrors make up the primary

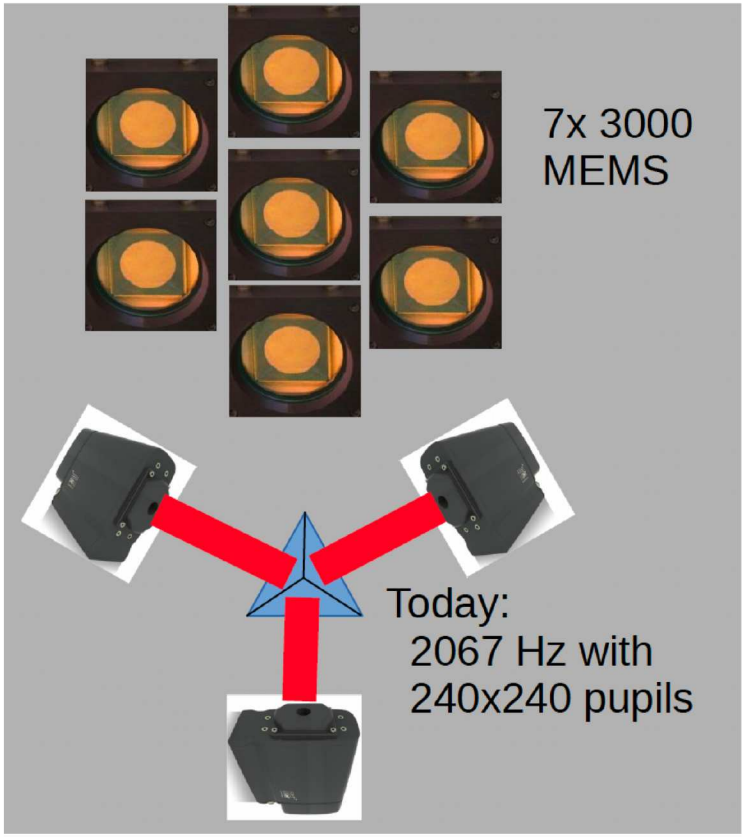


Artist rendering of the Extremely Large Telescope (ELT).

THE GIANT MAGELLAN TELESCOPE EXTREME ADAPTIVE OPTICS SYSTEM: GMAGAO-X

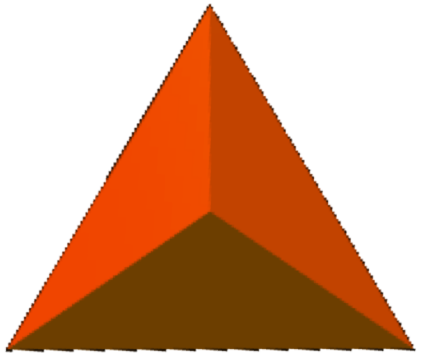
- 7x 3,000 actuator deformable mirrors
- 3 OCAM2K detectors
- 240 x 240 mode 2kHz on OCAM2k





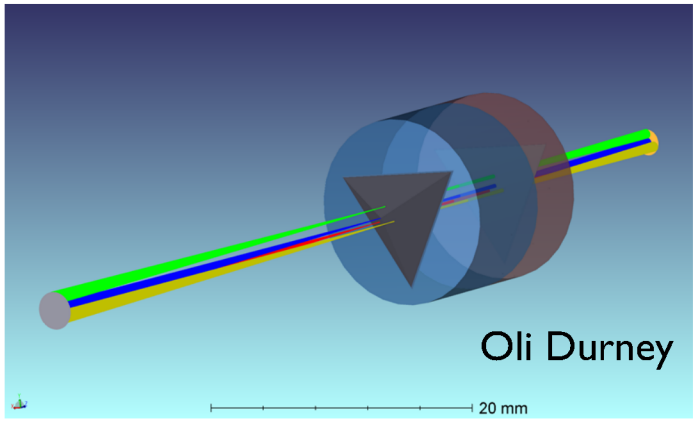
THE 'THREE'AMID WAVEFRONT SENSOR

- Starting with a refractive 3PWFS
- How to treat the wavefront sensor signals
- Sensitivity
- Overall Performance



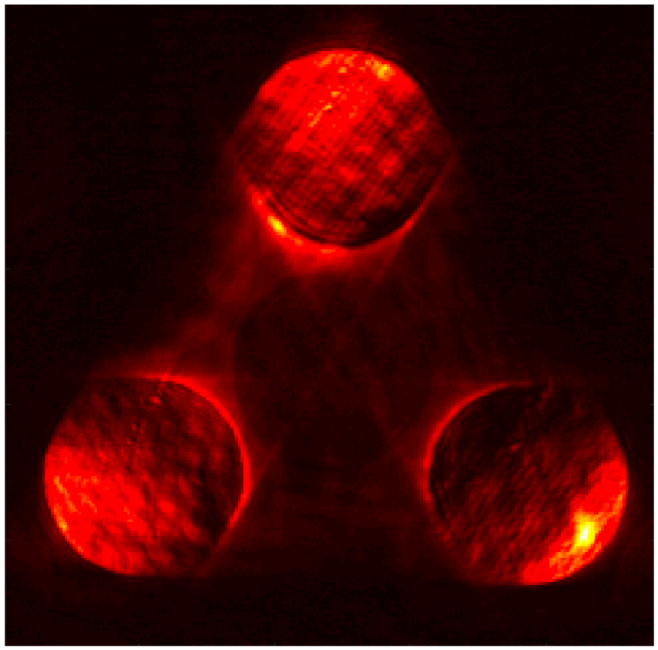
Some Benefits:

- Easier to Manufacture
- Less pixels=less sensitive to read noise
- Simpler than a reflective 4PWFS

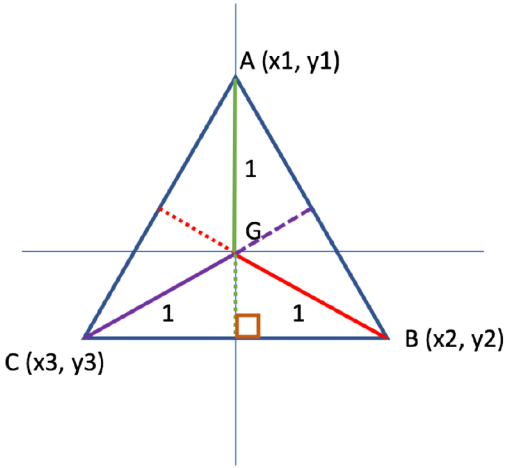


HOW TO TREAT THE SIGNALS

Schatz et. al. in prep



Centroid Equation for an equilateral triangle with the center at the origin



Slopes Map Equations

$$S_x = \frac{I_2\left(\frac{\sqrt{3}}{2}\right) - I_3\left(\frac{\sqrt{3}}{2}\right)}{I_1 + I_2 + I_3}$$

$$S_y = \frac{I_1 - I_2\left(\frac{1}{2}\right) - I_3\left(\frac{1}{2}\right)}{I_1 + I_2 + I_3}$$

4-sides

$$S_x = \frac{I_1 + I_2 - I_3 - I_4}{I_1 + I_2 + I_3 + I_4}$$

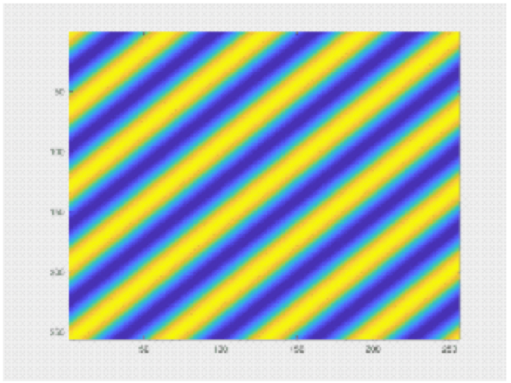
$$S_y = \frac{I_1 - I_2 - I_3 + I_4}{I_1 + I_2 + I_3 + I_4}$$

Or: Use the Full Frame Method

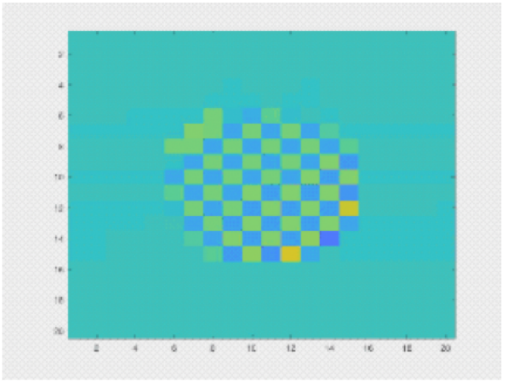
SENSITIVITY AS A FUNCTION OF SPATIAL FREQUENCY

Schatz et. al. in prep

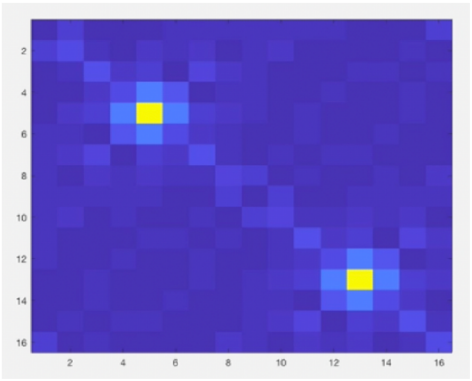
Input FM Mode



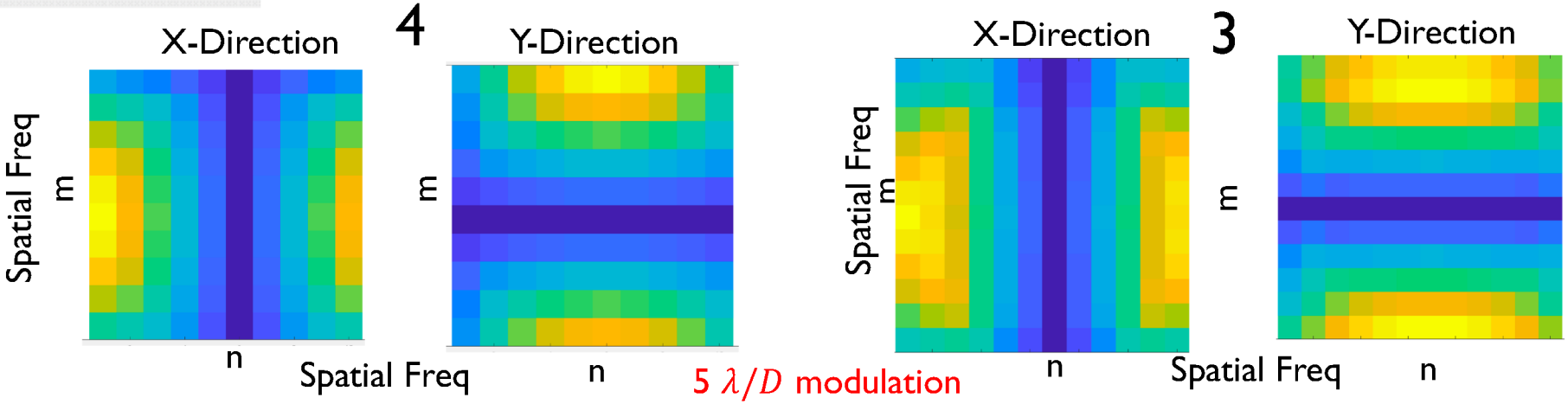
Compute slopes



Fourier Transform



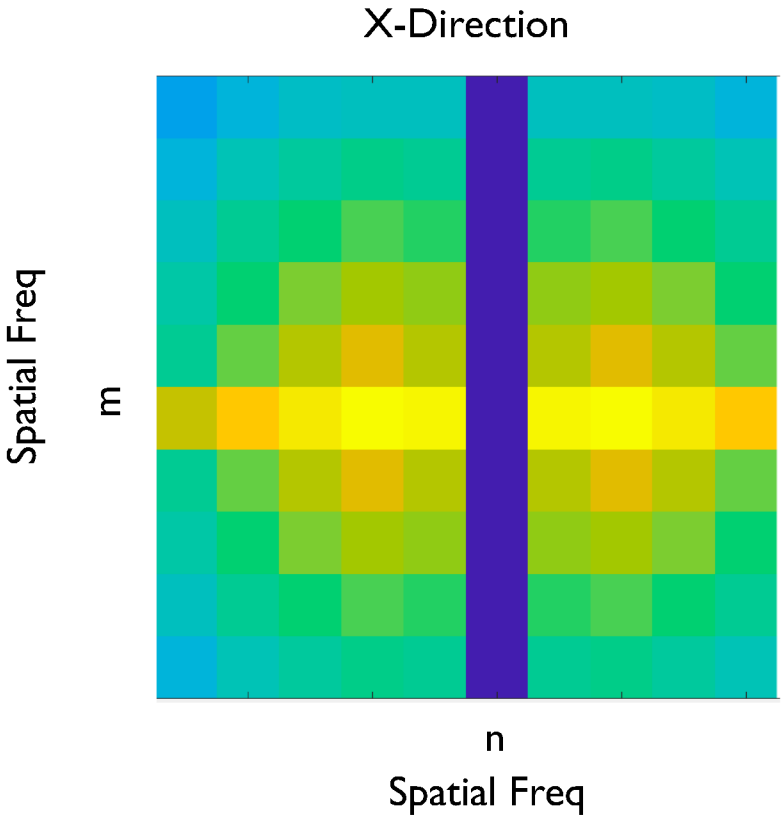
Result: 2D Fourier Sensitivity Map

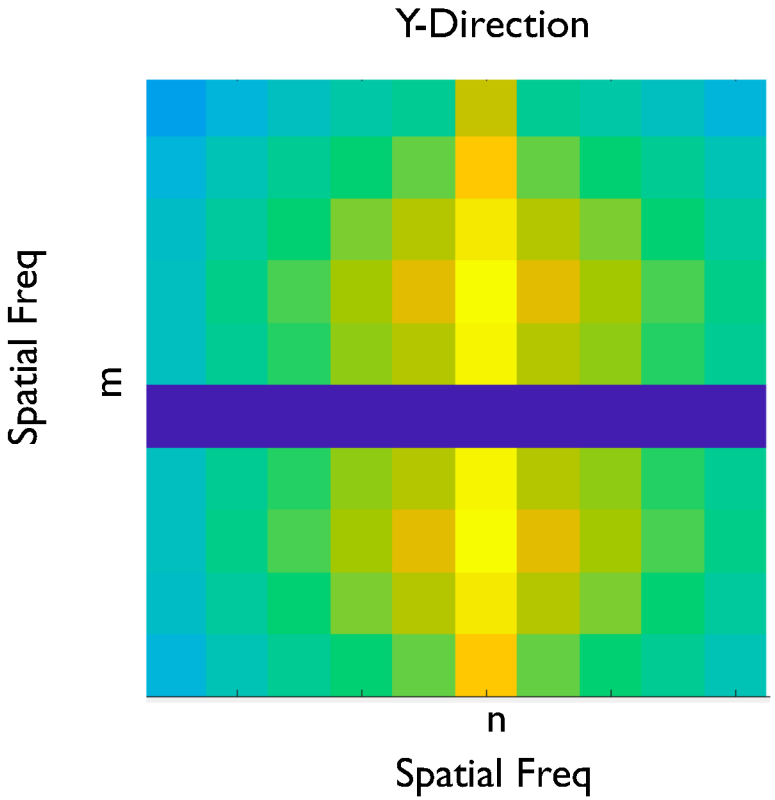


5 λ/D modulation

4PWFS NO MODULATION

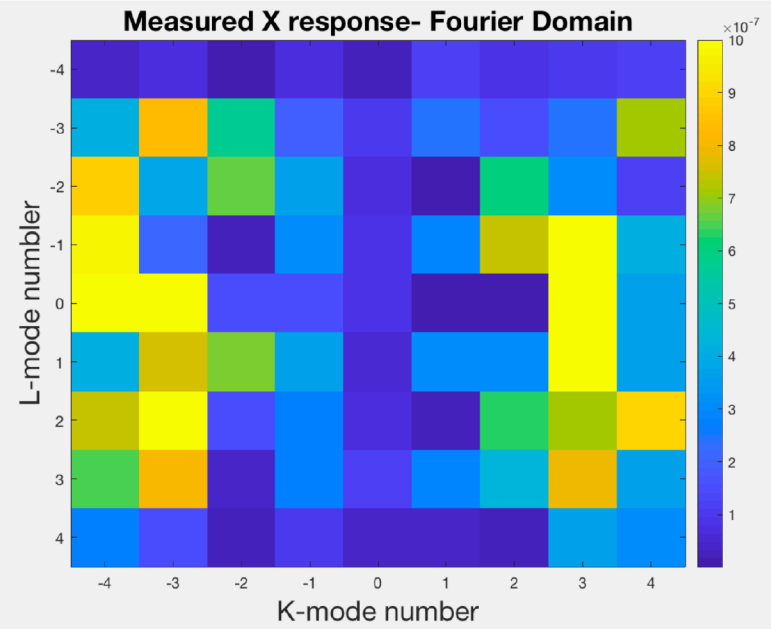
Schatz et. al. in prep



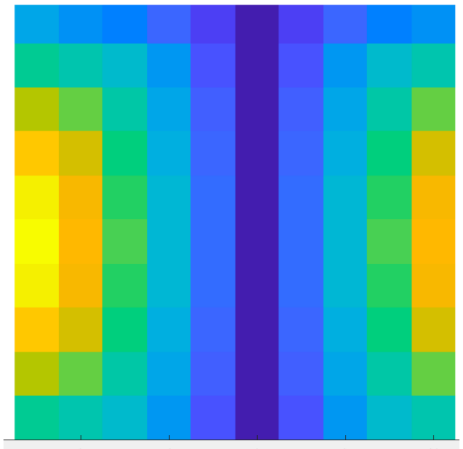


MEASURED RESULTS-Y

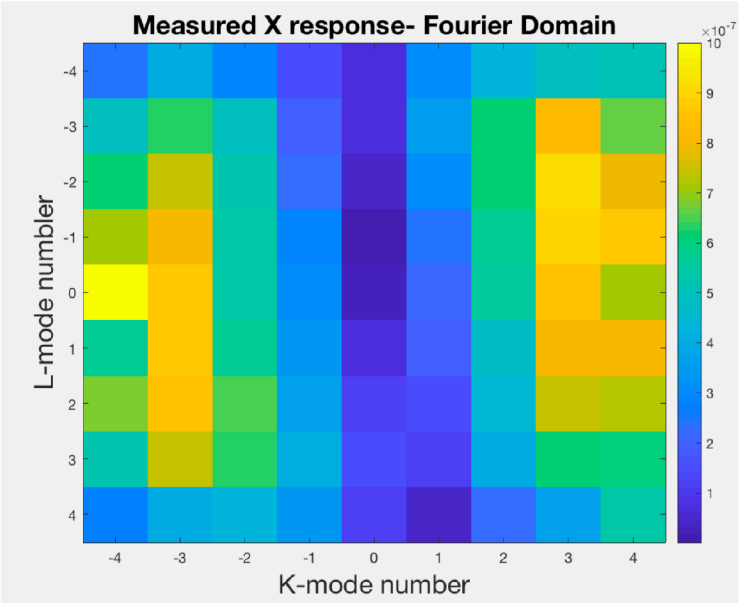
4PWFS



Simulated



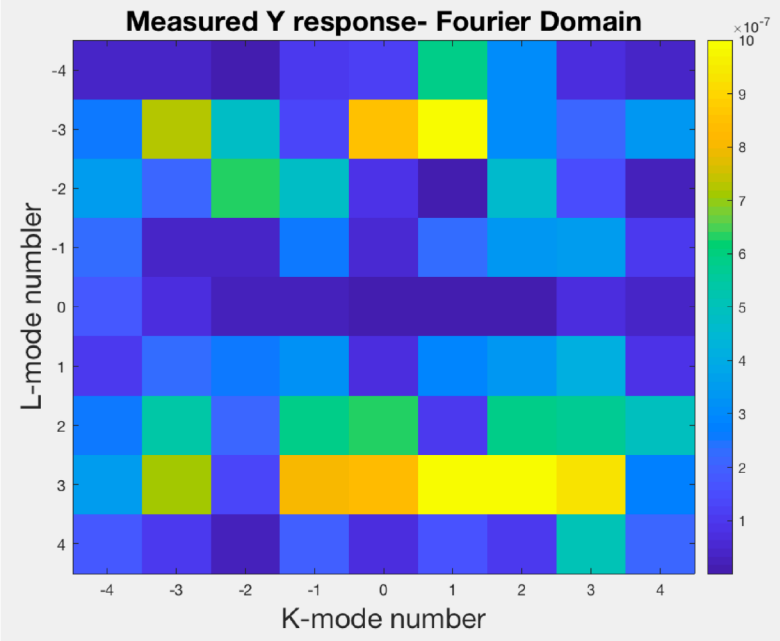
3PWFS



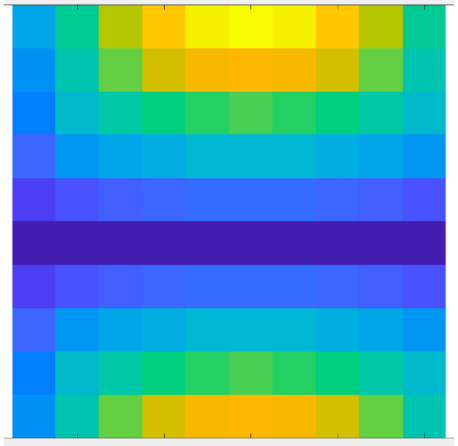
Normalized by Flux at each Spatial Frequency

MEASURED RESULTS- Y

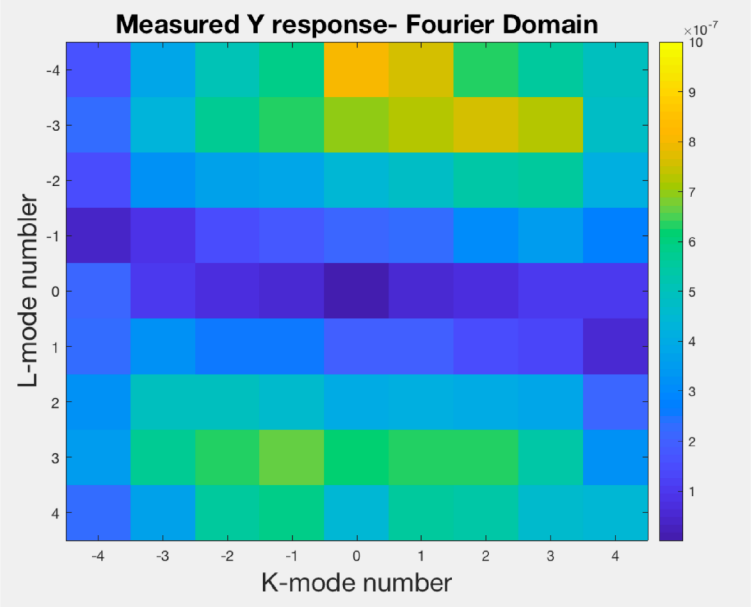
4PWFS



Simulated



3PWFS

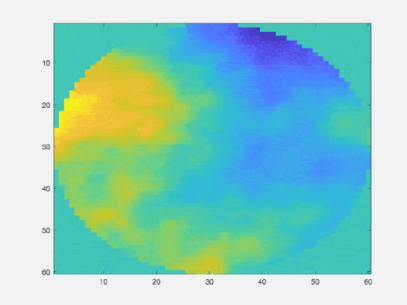


Normalized by Flux at each Spatial Frequency

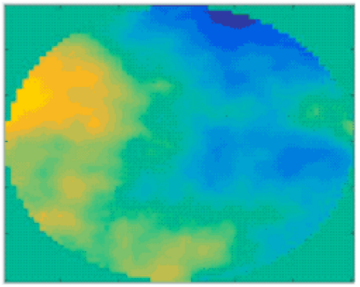
OVERALL PERFORMANCE

Schatz et. al. in prep

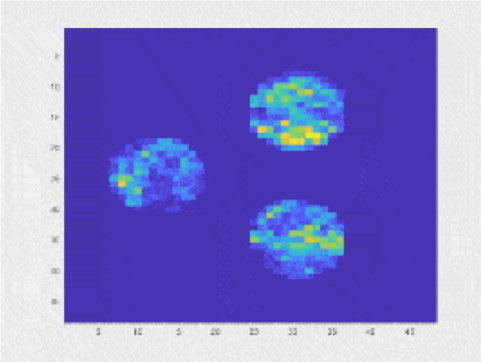
- End to end simulations done using OOMAO
- 2 m telescope
- R_0=6cm
- 1 phase screen moving at 7.4 m/s
- 8 DM actuators
- 20 pixels across each pupil



Input phase screen

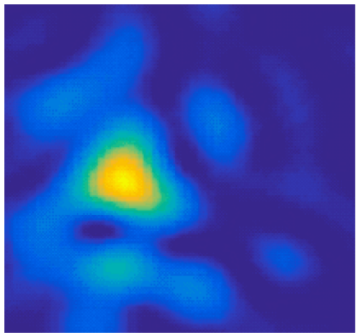


Residual phase

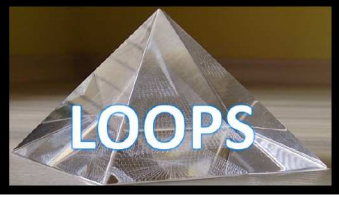


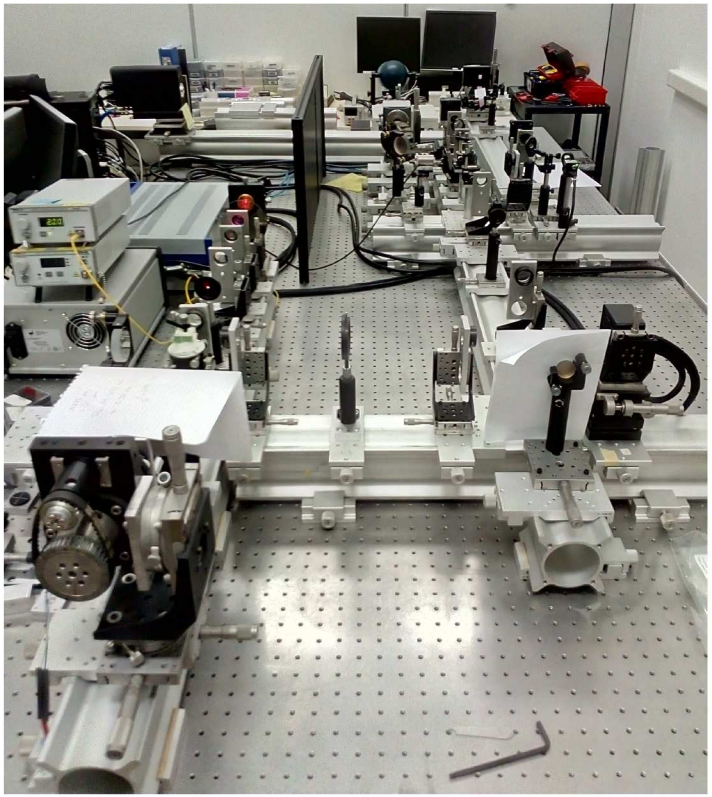
WFS camera

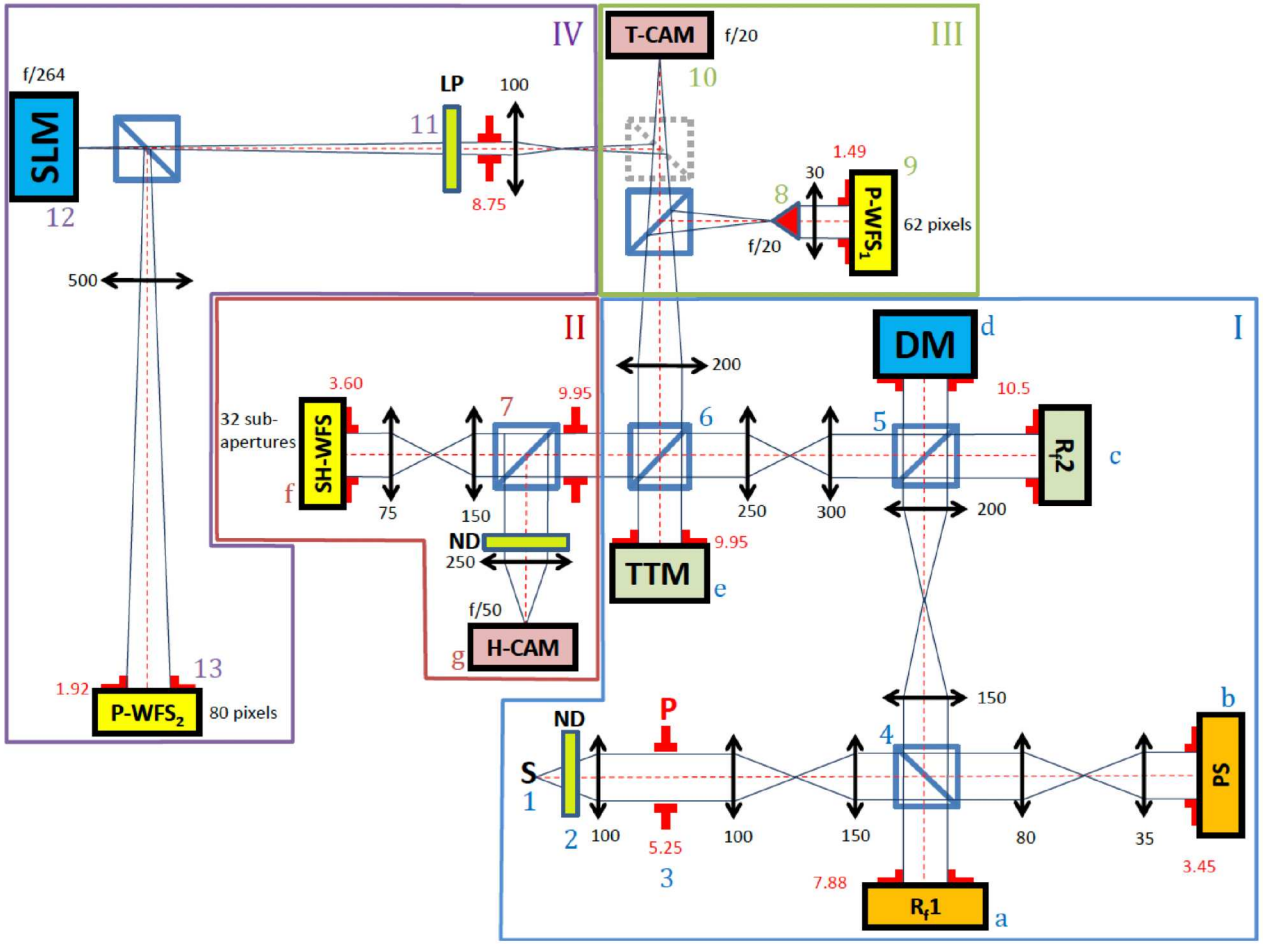
$5\frac{\lambda}{D}$ modulation



PSF


LOOPS




IV
III
II
I
f/264
SLM
12
LP
100
11
8.75
500
T-CAM
f/20
10
1.49
30
8
9
P-WFS1
62 pixels
f/20
DM
d
10.5
Rf2
c
200
200
3.60
32 sub-
apertures
SH-WFS
f
75
7
9.95
150
6
250
300
5
ND
250
9.95
TTM
e
f/50
H-CAM
g
1.92
13
P-WFS2
80 pixels
ND
P
S
1
2
100
5.25
3
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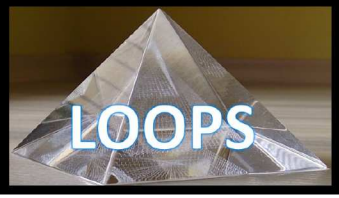
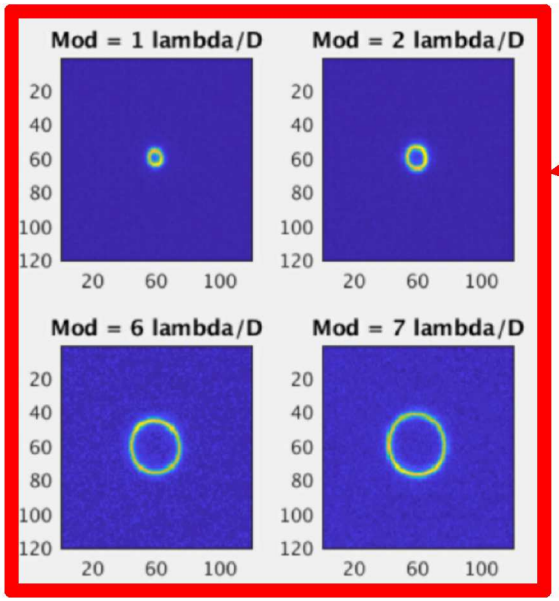
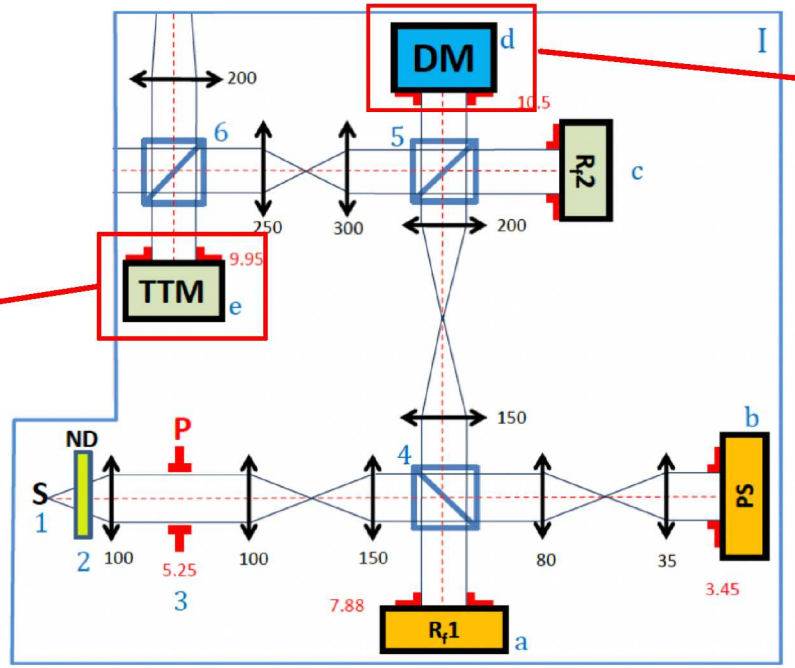
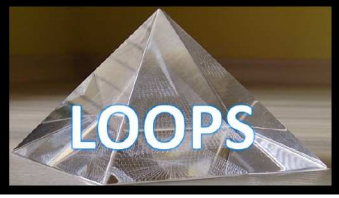
150
4
150
80
35
b
PS
3.45
7.88
Rf1
a



- Fiber Source
- Reflective Phase Wheel
- Alpao69
- Modulation Stage

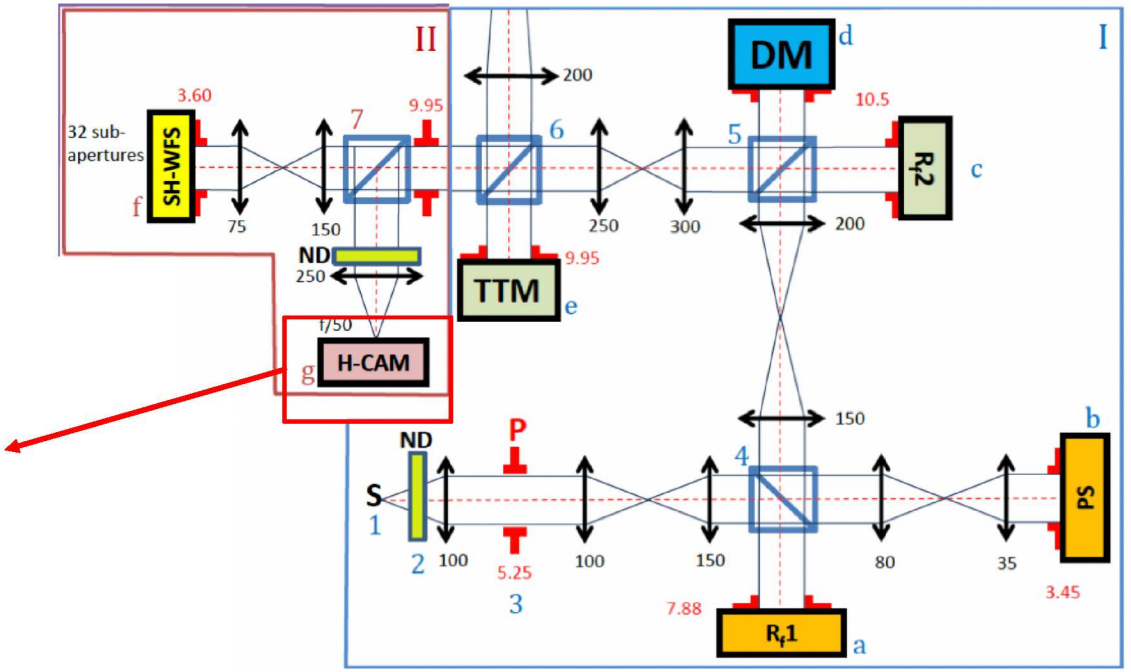


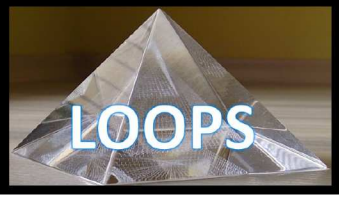




- 32x32 Shack Hartmann
- Hamamatsu ORCA-Flash CMOS science camera

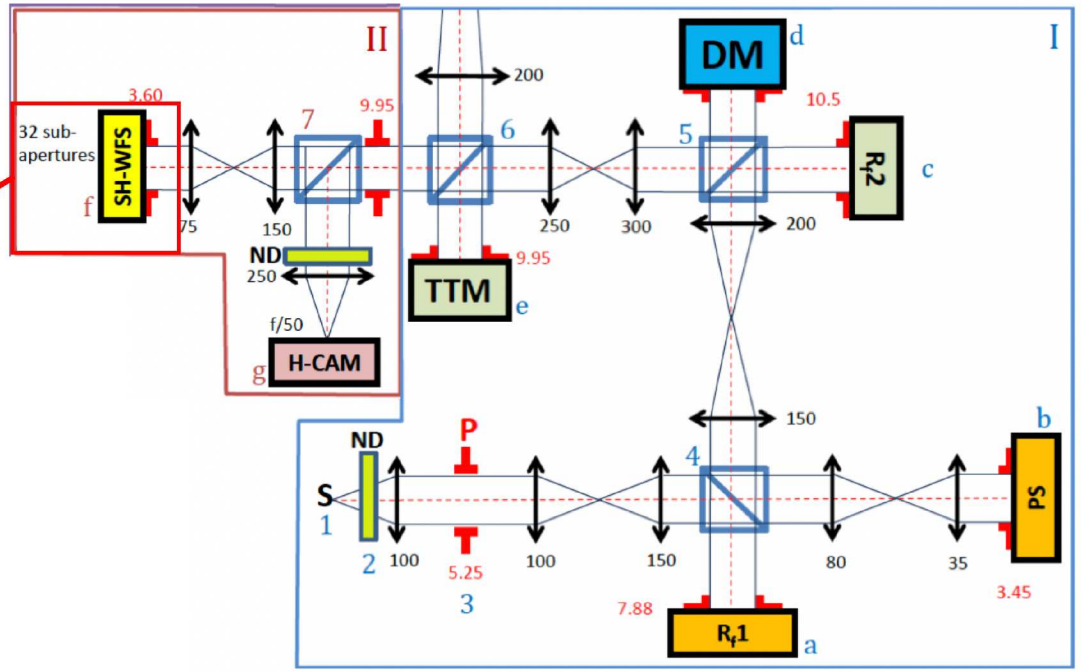
Can Measure Strehl





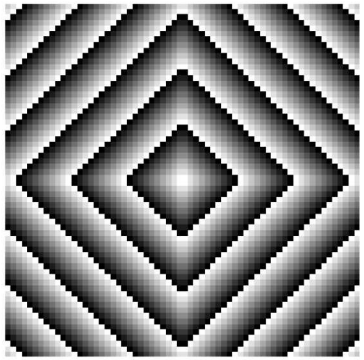
- 32x32 Shack Hartmann
- Hamamatsu ORCA-Flash CMOS science camera

Can Measure Residual Wavefront

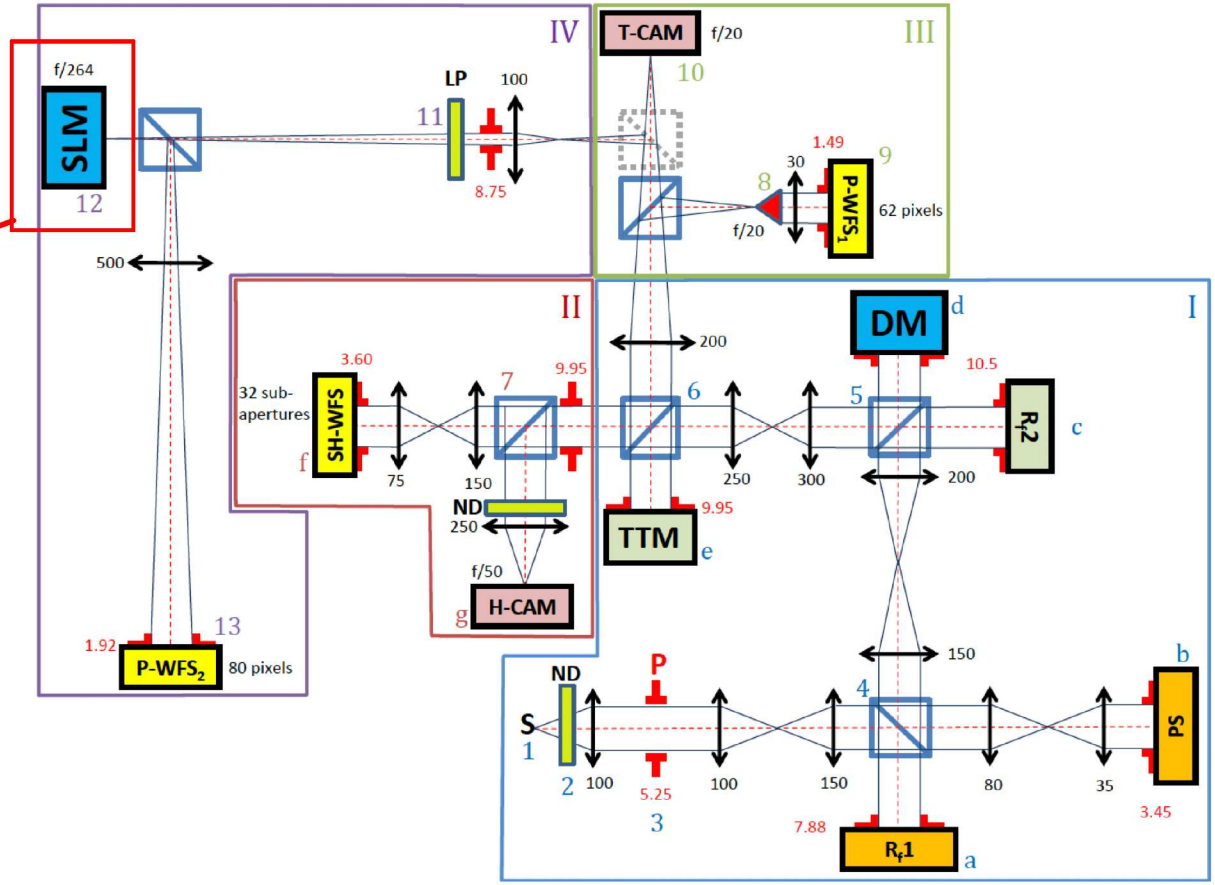


Place in Focal Plane

Spatial Light Modulator



Phase mask



NEW WAVEFRONT SENSORS ON LOOPS

3PWFS

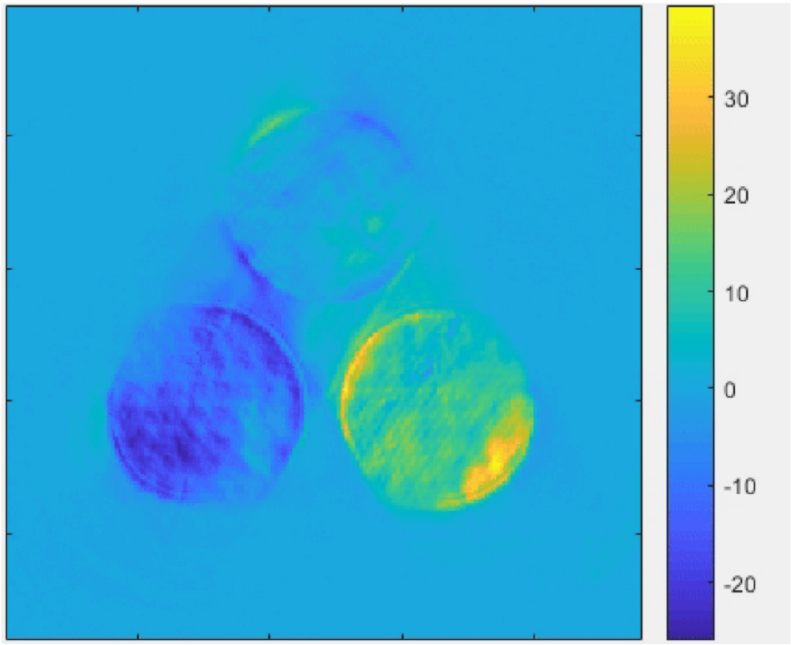
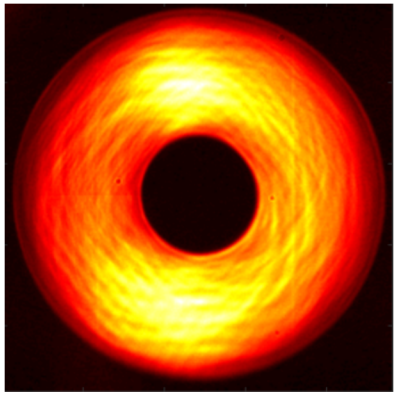
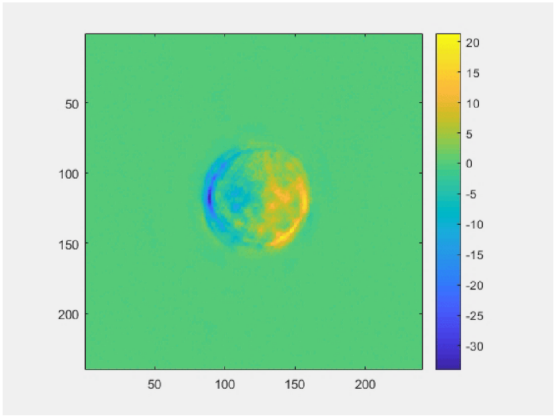


Photo: Credit Pierre Janin-Potiron

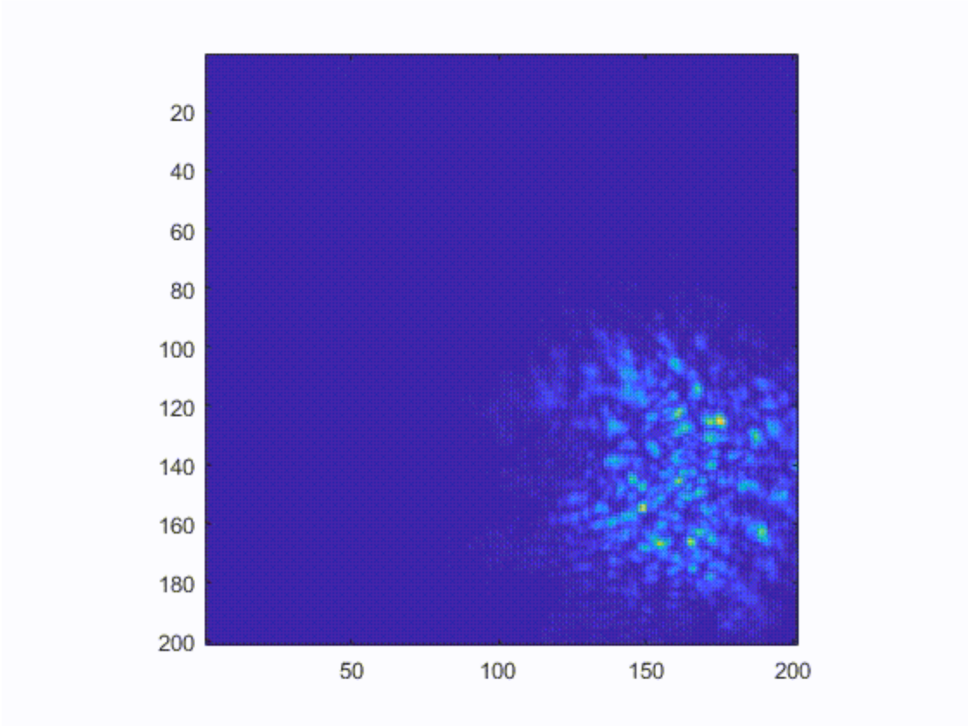


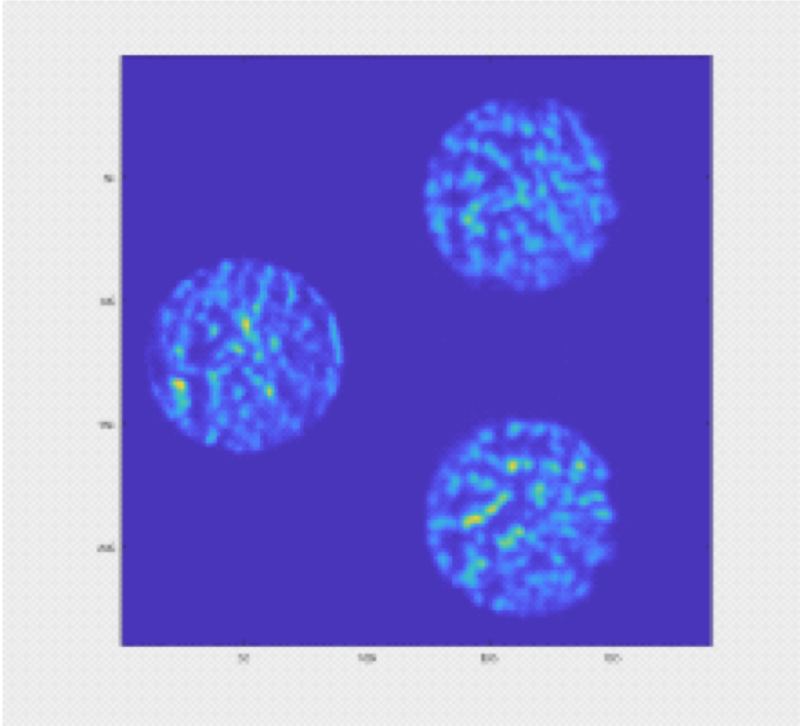
Axicone



Flattened

FIRST MILESTONE: CLOSED LOOP ON THE 3PWFS!!

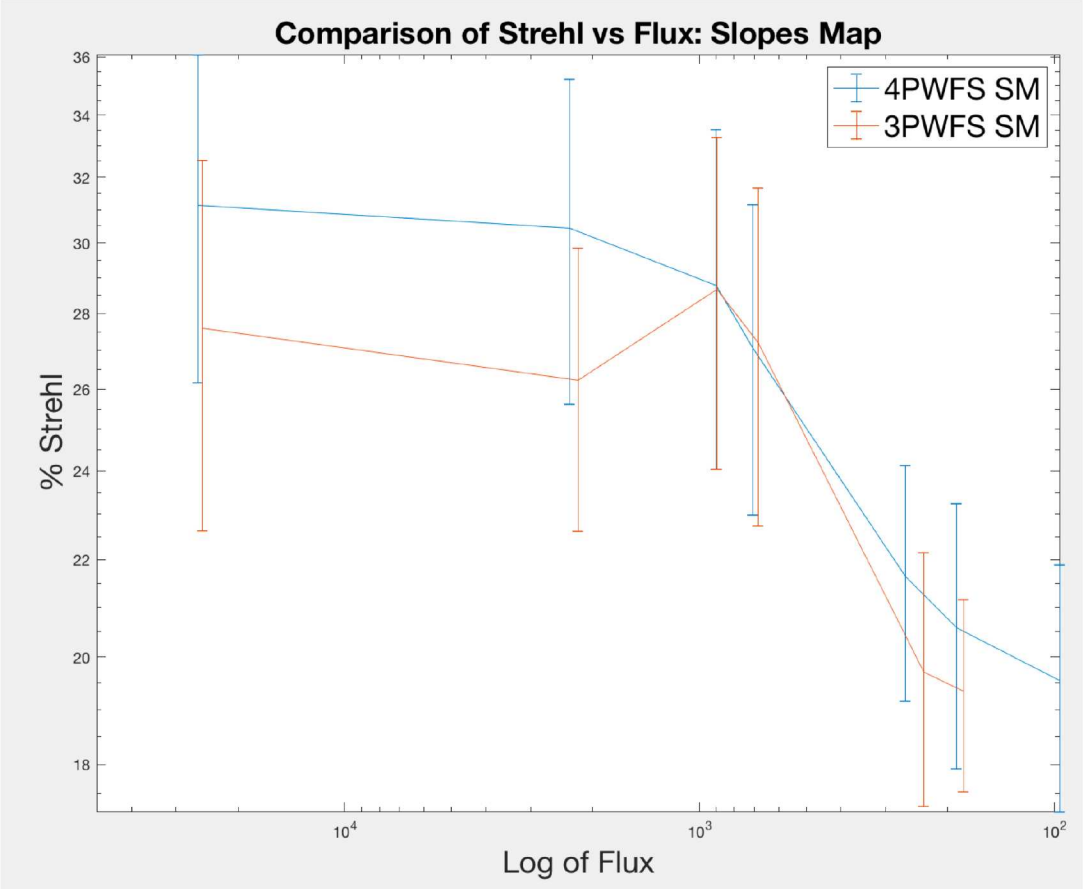




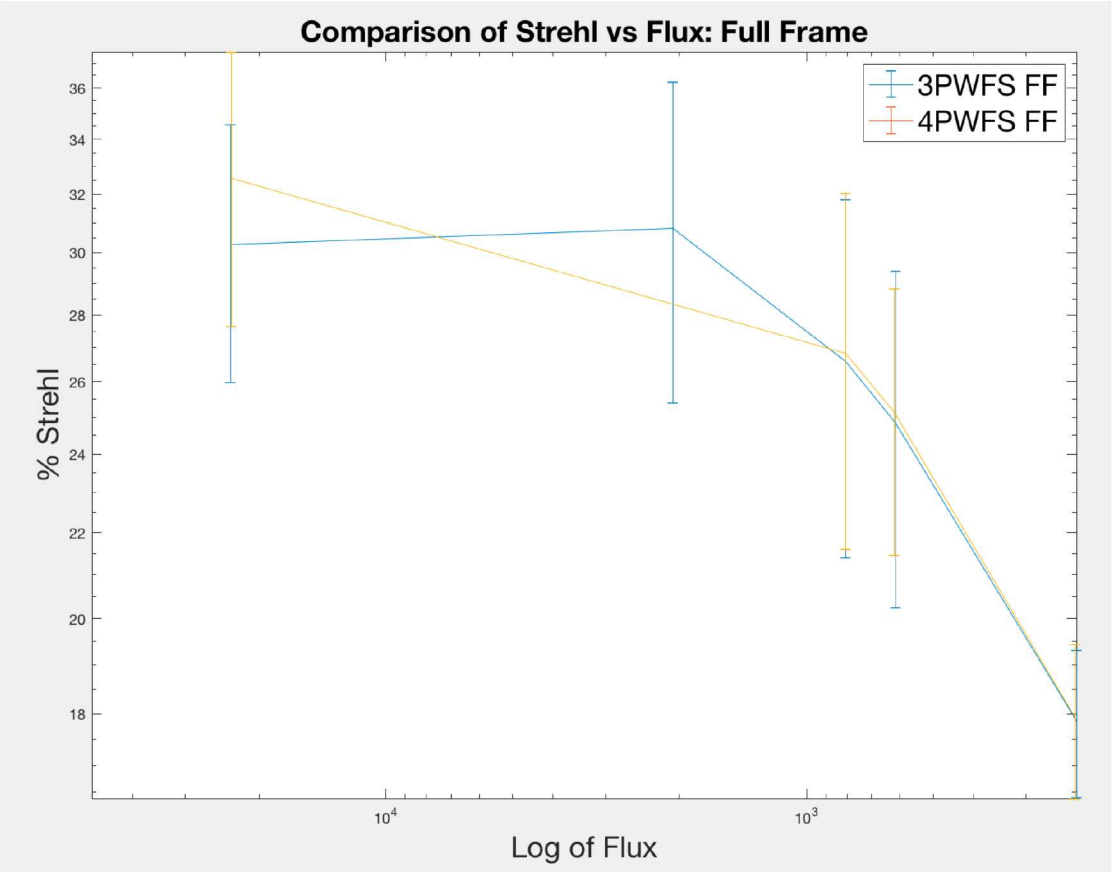
END TO END PERFORMANCE EXPERIMENTAL DETAILS

- Closed Loop at different levels of flux on the OCAM
  - Used a ND filter wheel to vary light
- Tried different Reconstructor: Full Frame, Slopes Maps
- At each step:
  - Took ~3 minutes of Shack Hartmann Data
    - Mean RMS Residual Wavefront
    - Zernike Decomposition of the Residual Wavefront
  - Took 2048 images of the PSF on the Hamamatsu
    - Calculated Strehl for each image, took the mean value.
  - Recorded the Flux on the detector from an average of 2000 frames, only considered light in the pupils. (Used a flat wave front, no turbulence.)

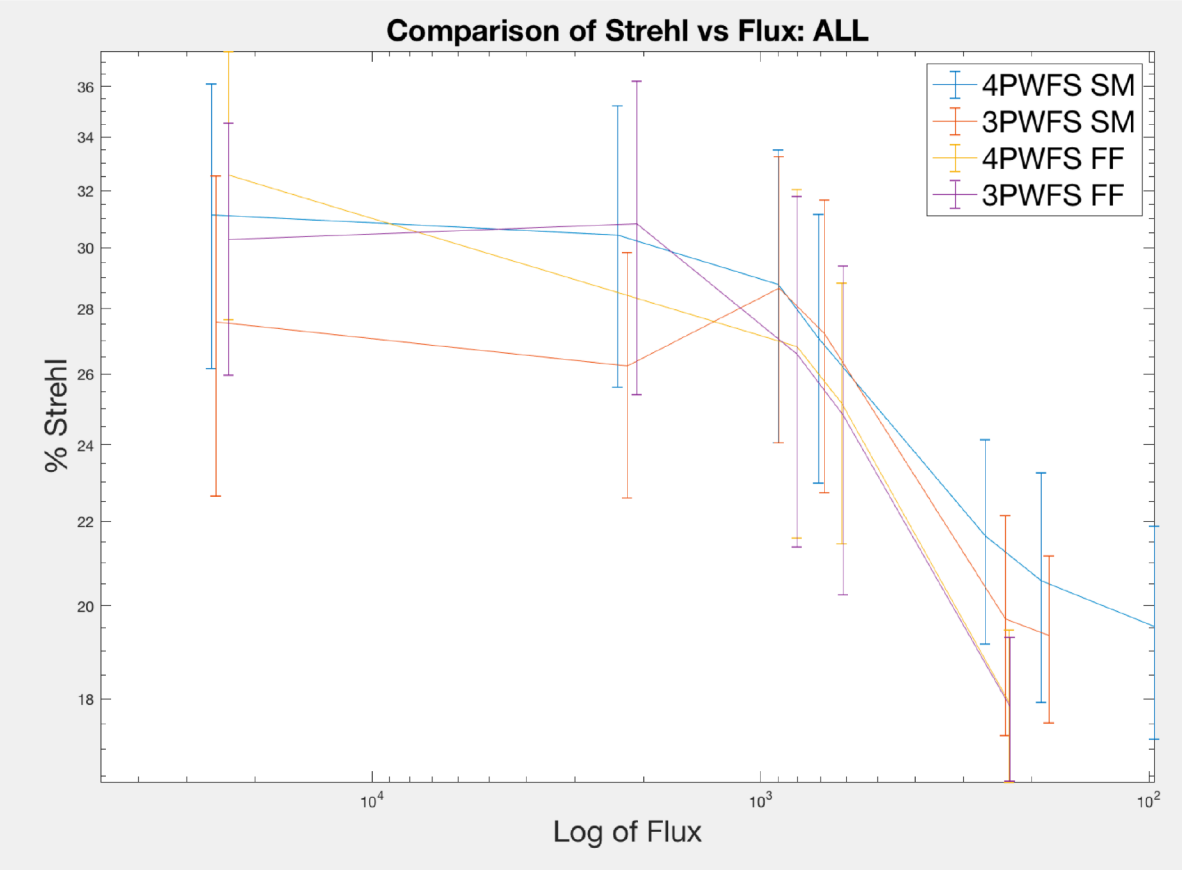
STREHL VS FLUX SLOPES MAPS



STREHL VS FLUX FULL FRAME



STREHL COMPARISON: AND FINAL CONCLUSIONS



Based on Mean: Full Frame is better

Performance of the Full Frame 3PWFS vs 4PWFS very similar

- Error bars high- need to take more data

SPECIAL THANKS

My Team Here: Benoit Neichel, Thierry Fusco, Carlos Correia, Pierre Janin-Patiron, Vincent Chambouleyron, Olivier Fauvarque

My Friends I have made here: Jana, Jorge, Sean, Elodie … the list goes on

My advisor Jared Males for being cool with letting me come here

4PWFS

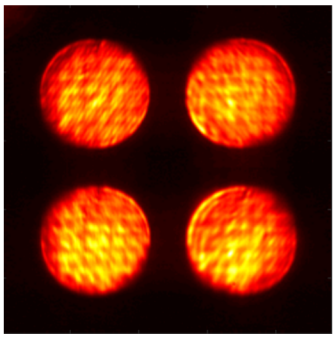
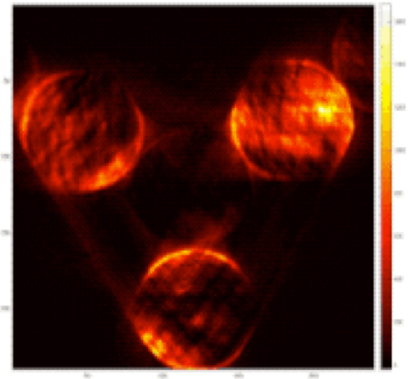


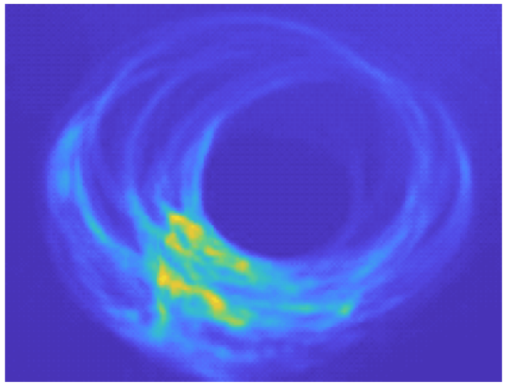
Photo: Credit Pierre Janin-Potiron

3PWFS

Real time on the SLM!

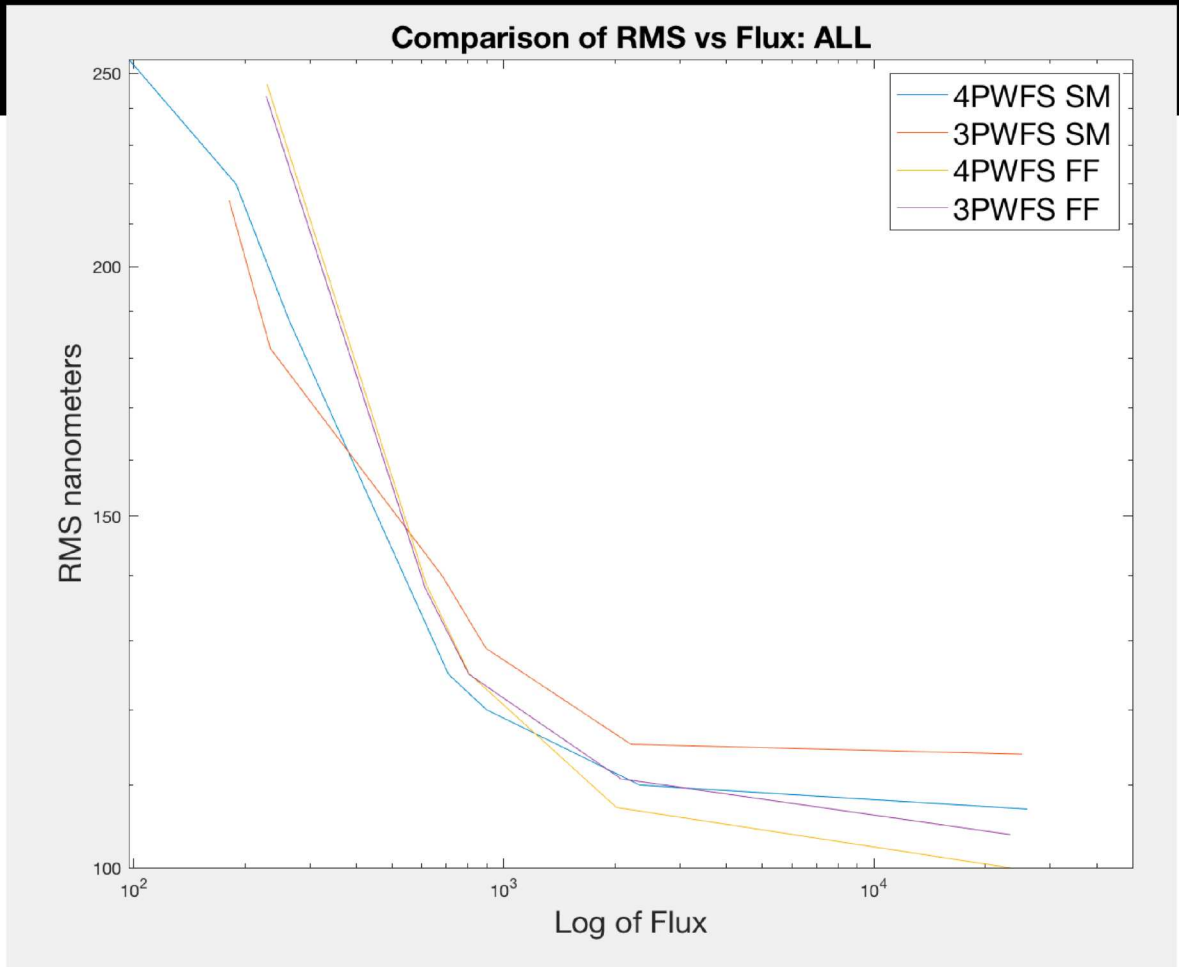


Axicone



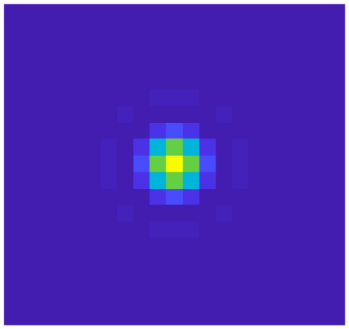
CANNED SLIDES

RMS VS FLUX

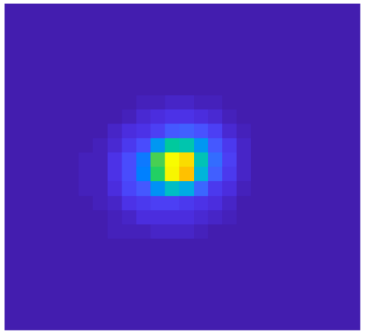

Comparison of RMS vs Flux: ALL
4PWFS SM
3PWFS SM
4PWFS FF
3PWFS FF
RMS nanometers
250
200
150
100
10^2
10^3
10^4
Log of Flux

END TO END TESTS: 4PWFS

Perfect Simulated

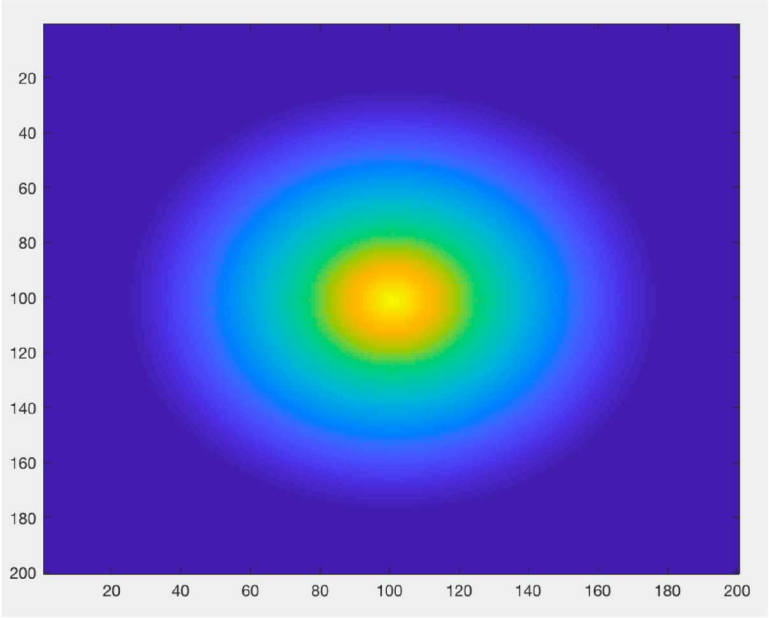


Perfect Bench

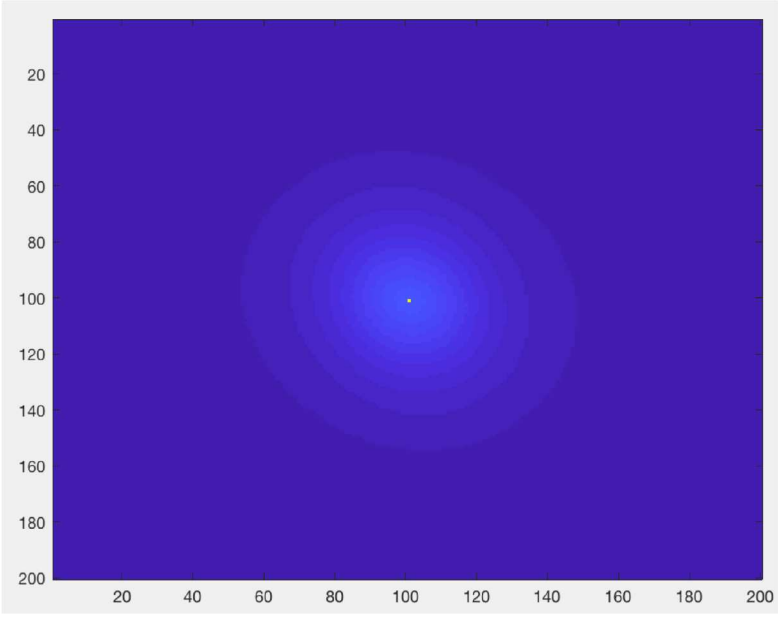


OTFS

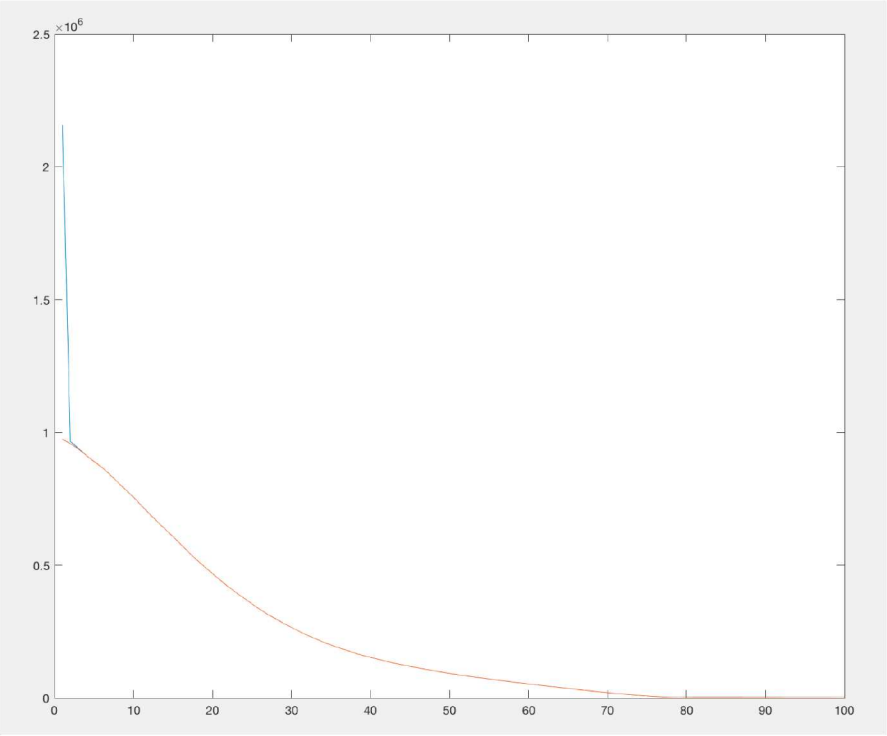
Perfect Simulated

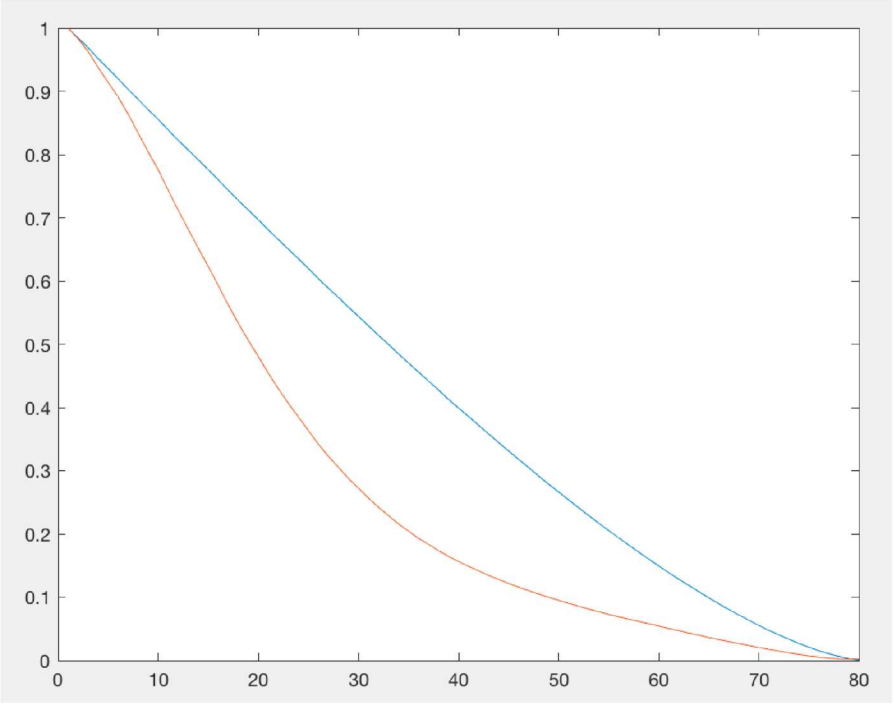


Perfect Bench OTF



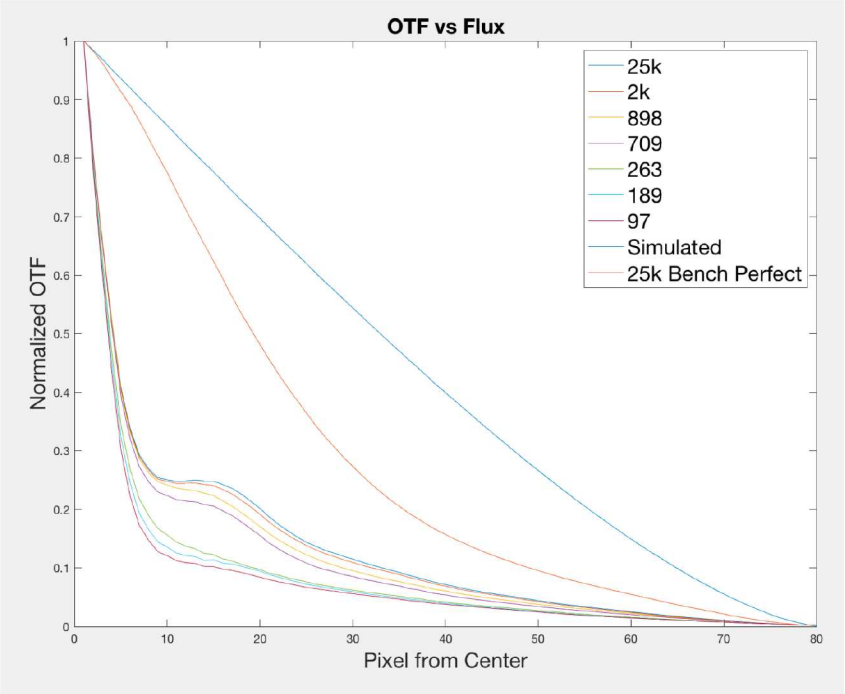
OTF FITTING


×10^6
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
90
100

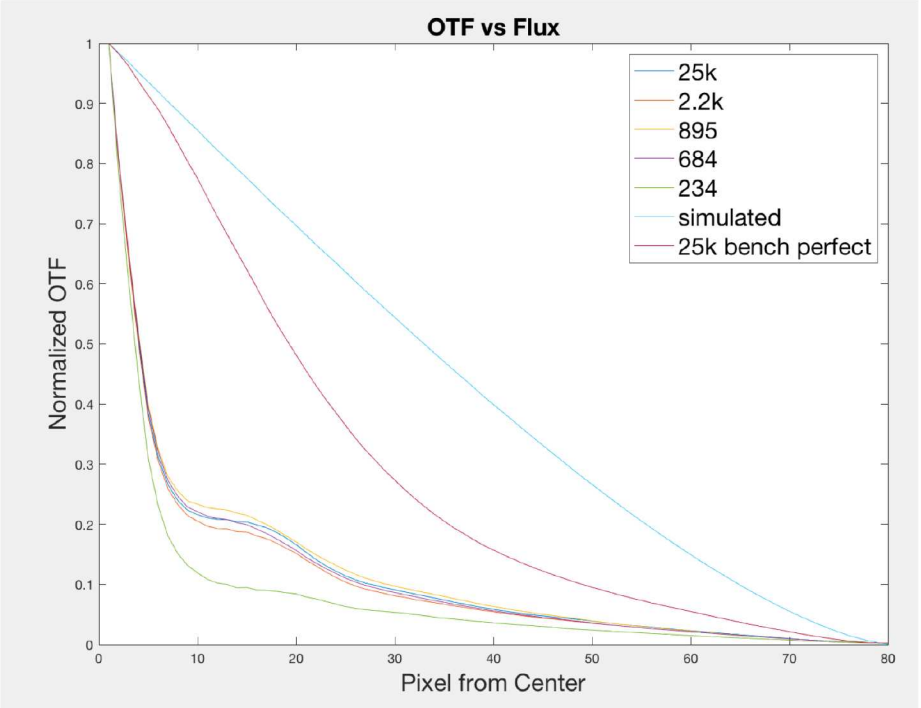

1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
60
70
80

RESULTS: SLOPES MAPS

4PWFS

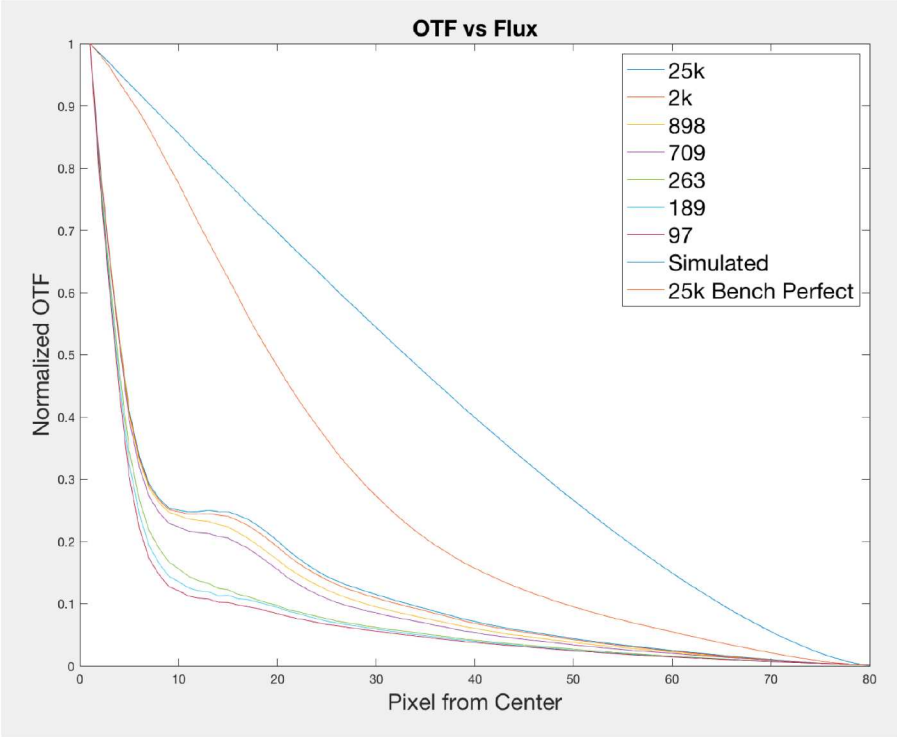


3PWFS

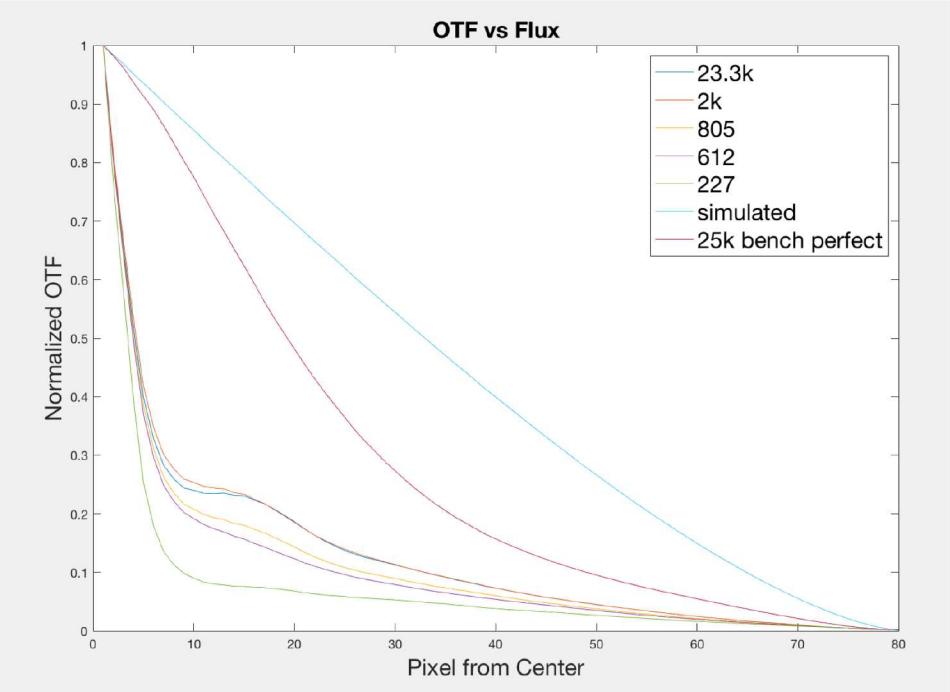


RESULTS: FULL FRAME

4PWFS



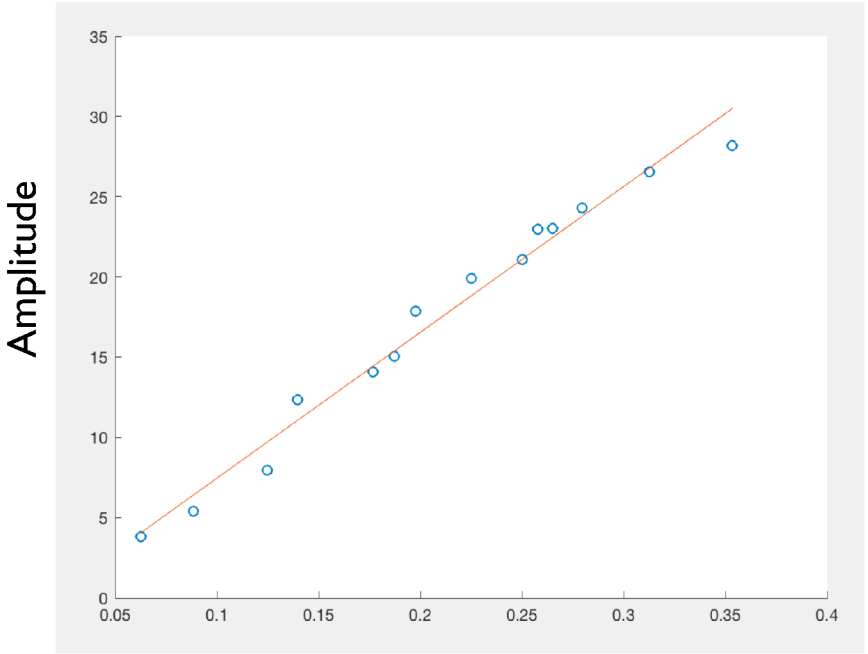
3PWFS



MATHEMATICS OF WAVEFRONT SENSORS

- Derivative wavefront sensor: Linear with spatial frequency
  - $\phi(k) \propto Asin(kx)$
  - $\frac{d}{dx}\ \phi(k) \propto Akcos(kx)$

Shows the linear relation of the SH to K



4PWFS

Shift from measurement point (CCD pixel) to reconstruction point (actuator)

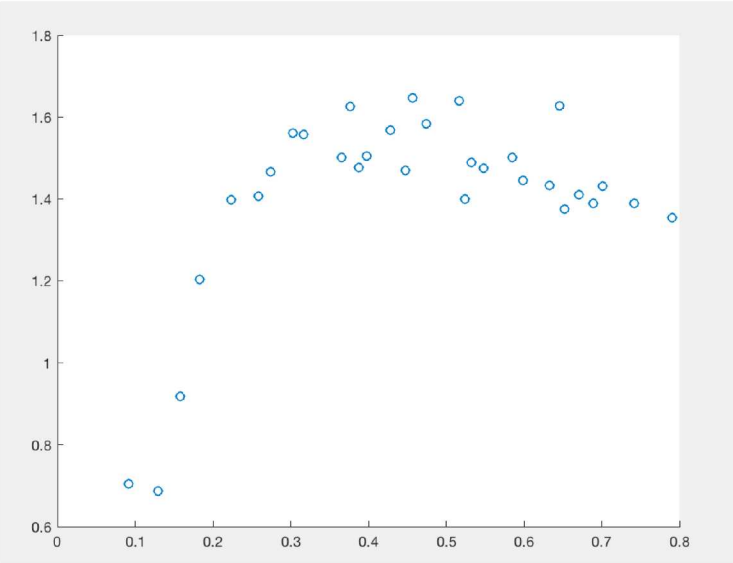
Pixel averaging (discrete process)

Flat response

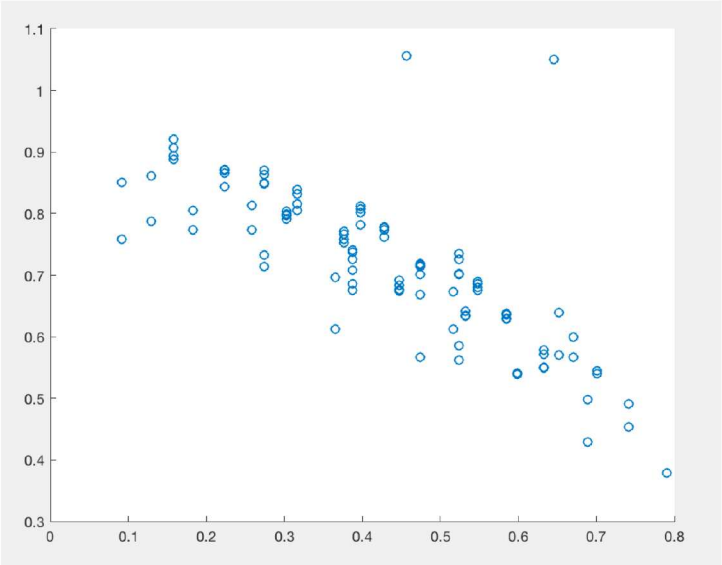
$$\tilde{G}(\kappa) = e^{\mathrm{i}\pi d(\kappa_x+\kappa_y)}\operatorname{sinc}(d\kappa_x)\operatorname{sinc}(d\kappa_y)\begin{cases}\mathrm{i}\ \operatorname{sgn}(\kappa), & |\kappa| > \kappa_{\mathrm{mod.}}\\ \frac{2\mathrm{i}}{\pi}\sin^{-1}\frac{\kappa}{\kappa_{\mathrm{mod.}}}, & |\kappa| \le \kappa_{\mathrm{mod.}}\end{cases}$$

Modulated response

Credit: Charlotte Bond



5 mod



0 mod